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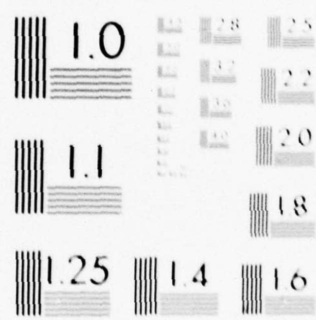

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DEVICES FOR FIBER OPTICS COMMUNICATION

ITT Electro-Optical Products Division
P. O. Box 7065
Roanoke, Va 24019

December 1978
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AIR FORCE AVIONICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report is the final report on a one-year technology development program for fiber optic coupler components. The devices investigated and developed were three port couplers, directionals and "T" couplers, and reflective and transmissive star couplers with 7, 19 and 32 ports or port pairs respectively.

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These coupler components were fabricated by direct fusion of plastic clad silica (PCS) fiber cores. Power division or distribution in these couplers is proportional to the ratio of the area of any port to that of the total coupler cross-sectional area, termed area ratio splitting.

Directional couplers with -3.0 dB and -13.0 dB tap-off levels were fabricated. For the -3 dB design, excess loss of less than -1 dB was achieved routinely; minimum excess loss was 0.22 dB. For the -13 dB design, actual tap-off levels ranged from -14 dB to -16 dB. The excess loss ranged from -0.7 dB to -1.0 dB.

The directional couplers investigated were also assembled to form "T" couplers of the same design tap-off levels. The excess losses in these components were higher than expected, due to a modal redistribution phenomenon in the constituent directional couplers, each with its own specific modal redistribution signature. This phenomenon was more strongly evident in the even split "T" coupler design. Excess loss in these components ranged from -2.5 dB to -5.0 dB, typically.

Due to the form of the star couplers and the fixturing and packaging concepts employed, the fabrication of reflective star couplers was not successful. Processing steps after the fusion of the coupler caused all devices to fail.

Star couplers of the transmissive variety achieved excess loss of less than -3 dB, -5 dB and -7 dB respectively for the 7, 19 and 32 fiber models. The uniformity of the seven-fiber model was well within ±1 dB. It appears that further improvements in performance will result from fabrication technique improvement, device fixturing, and packaging which minimizes externally induced stresses.

FOREWORD

This final report summarizes the twelve months of work performed on Air Force Contract F33615-77-C-1058 entitled, "Devices for Fiber Optics Communication." This work was performed from April 15, 1977 to May 14, 1978. This report was prepared by the Electro-Optical Products Division of ITT and describes work performed by Mr. Larry Foltzer.

The work performed under this contract was administered by the Air Force Avionics Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. Mr. E. R. Nichols (AFAL/DHO) is the technical representative for the Avionics Laboratory. This report was submitted by the authors in October 1978.

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SECTION I

INTRODUCTION

This report is the final report of a one-year technology development effort on coupling devices for fiber-optic data bus systems. Specifically the work reported here was performed under contract number F33615-77-C-1058 from the Air Force Avionics Laboratory at Wright-Patterson Air Force Base.

The devices developed under this program are efficient branching couplers consisting of both directional and "T" couplers and efficient central distribution couplers consisting of reflection and transmission distribution mixers (sometimes called stars).

The basic approach to fabricating couplers for this program is to form the coupler region directly by fusing bare plastic clad silica (PCS) fiber cores together. The approach was chosen on the basis of an analysis performed prior to the start of the program which indicated, at least for data bus applications, that area-ratio splitting techniques would be suitable for constructing efficient couplers. By using bare cores of PCS fibers it is possible to eliminate the core/cladding ratio losses inherent in using other fiber types in an area-ratio splitting configuration.

High coupling efficiency is obtained by maintaining the total coupler cross-sectional area throughout the coupler region. In effect, even though the cross-sectional geometry is changing, the effective mode volume is maintained. By transitioning slowly enough from a single fiber to multiple fibers, excess losses are minimized. The slow transitioning of individual fiber shape into the fused region containing more than one fiber eliminates the packing fraction problem that contributes significant excess loss in couplers using area-ratio-splitting implemented by individual, separated mixer regions.

Since the actual performance of couplers fabricated by direct fusion of individual fiber cores is expected to depend significantly on the fusion technique, the major emphasis in this program was on developing the techniques required to produce efficient couplers. As will be detailed in later sections it was found that fiber and materials preparation had a significant impact on the ability to produce good fusions. It appears that the geometrical configuration in which the fusion was performed had a significant impact on coupler excess losses. The results of the effort to develop and refine the relevant processing and fusion techniques and the coupler performance that resulted from this effort are reported in the following sections. Specifically the general processing and fusion technique considerations relevant to all coupler types are reported in Section II. Sections III through V detail the special techniques and processing relevant to directional couplers, "T" couplers, and stars, in that order. Specific conclusions with respect to each coupler type are contained in the relevant section. Finally general conclusions and recommendations for additional effort are discussed in Section VI.

SECTION II

GENERAL COUPLER CONSIDERATIONS

In this section, the factors influencing the selection of the fiber size for coupler fabrication, cladding materials selection, fiber preparation and fabrication techniques common to all couplers developed under this program are discussed. In Section II, 7, techniques for installing connectors on PCS fibers using reflective silver coatings are described. Section II, 8, describes the measurement apparatus used for coupler characterization during this program.

1. Selection of Fiber Size

The choice of the transmission line fiber size can be expected to affect the practical maximum splitting ratios that can be attained for directional and "T" couplers.

The overall efficiency of couplers fabricated by implementing the area-ratio-splitting technique with direct fusion of fiber cores is directly related to the relative cross-sectional areas of the fibers used internal to the coupler and the transmission line fiber. Secondly, the problems encountered in handling and fusion of very small fibers with significantly larger fibers affects the ability to fabricate directional and "T" couplers with high splitting ratios.

On the other hand, the choice of transmission line fiber size to be used in a practical system will be dominated by the fiber transmission characteristics which are related to fiber size. Particularly, fiber minimum bend radius and susceptibility to microbend loss are both adversely affected as fiber core diameter increases. Consequently at the outset of this program it was necessary to make a reasoned choice as to fiber size to which the couplers would mate. At that time, PCS fibers with 127 μm and 203 μm cores were available, the former on a more-or-less routine basis and the latter on a special requirements basis. Because of the combination of microbend losses expected in the larger fiber, the relative availability of the smaller core fiber, and its relatively more compliant nature, the 127 μm fiber was chosen as the transmission line fiber to which the couplers would be required to mate. It should be noted that the techniques to be developed would be expected to be applicable to couplers designed to match the larger core fibers should they in fact be chosen for other reasons to be the transmission line fiber in a practical system. In addition couplers developed using PCS fibers internally can be expected to mate efficiently to glass-glass type fibers with the same core size and numerical aperture.

Once the transmission line fiber core size had been chosen, a choice needed to be made for the fibers to be used internal to the directional and "T" couplers (the fiber size for the distribution mixer couplers was automatically determined by the transmission line fiber). When one considers the various purposes for which directional couplers (and to a lesser extent "T" couplers) may be used, a large number of tap-off ratios and fiber size choices emerge. For example, a directional coupler may be used for power splitting or combining, as a bidirectional coupler to inject signal into and receive signal from the same transmission line fiber, or as a single power monitor coupler for source stabilization. In the last case typically a very high throughput/tap-off ratio is desired. In the bidirectional case maximum system efficiency is obtained for area emitting LED sources when the coupler arm fibers each have one-half the cross-sectional area of the transmission line fiber, while the greater directionality and coupling efficiency of a GaAs strip laser might show maximum system efficiency with some imbalance in the coupler arm cross-sectional areas.

In order to avoid a proliferation of required fiber sizes and consequent tap-off ratio design which would not necessarily be consistent with the fundamental objectives of this program, the decision was made to limit the range of directional and "T" couplers to be developed to the extremes. Specifically, the coupler development was limited to even-split devices and maximum practical throughput/tap-off ratio devices.

2. Fiber Cladding Materials

The basic material type used as a cladding substance on the fibers used in the program were silicone based resins. These materials are available from many sources, Dow Corning and General Electric in the U. S. and from Shin Etsu in Japan.

The material from Shin Etsu, KE-103, has been found to yield the lowest loss plastic clad pure silica core fibers. ITT PCS fibers are generally coated with this material. There are, however, other considerations with respect to the material to be used as a cladding on fibers destined for coupler fabrication. The factor of two to three increase in loss, worst case, as a result of the losses associated with the cladding material, is of little consequence to coupler fabrication since only a few meters length of fiber is required. The most important consideration is that of cladding strippability.

During the early phases of this program, a considerable amount of effort was directed toward developing techniques for removing the cladding. Moderate, but inconsistent, success was achieved on fibers coated with Shin Etsu KE-103, and GE 670 Silicone RTVs using C-105-HF silicone stripper (Manufacturer-McGean Chemical Co.). Fibers cladded with a mixture of these materials were no easier to strip. The best cladding material found, in terms of strippability, is Dow Corning's Sylgard 184 silicone RTV. This material can be stripped mechanically with ease, reliably and completely. The couplers fabricated during the later portion of this program, were cladded with this material exclusively.

3. Fiber Preparation

The fibers used for this program were in actuality coated with two jackets. The first is Sylgard 184, followed by a protective outer jacket of Hytrel. The mechanical stripping of the Hytrel jacket and silicone RTV cladding material is accomplished by the following technique.

The fiber to be stripped is placed in a groove, such that the silica fiber within the jacket and cladding lies below the top surface of the block containing the groove. See Figure 1. A razor blade is brought down in contact with the block, cutting edge perpendicular to fiber axis, and the fiber is rotated about its axis. This makes a single cut around the periphery of the fiber without actually contacting the fiber. Without lifting the blade, the blade angle of attack is now adjusted to be almost horizontal, and the fiber is drawn under the blade which cuts off a slice of the jacket from one side of the fiber over the desired length. Using finger cots, the jacket and in some cases the cladding can be peeled away from the fiber. At this point, the bare fiber is cleaned and the remaining RTV removed by pulling the fiber through a Kimwipe tissue "soaked" with a 50-50 mixture of isopropyl alcohol and Freon TF.

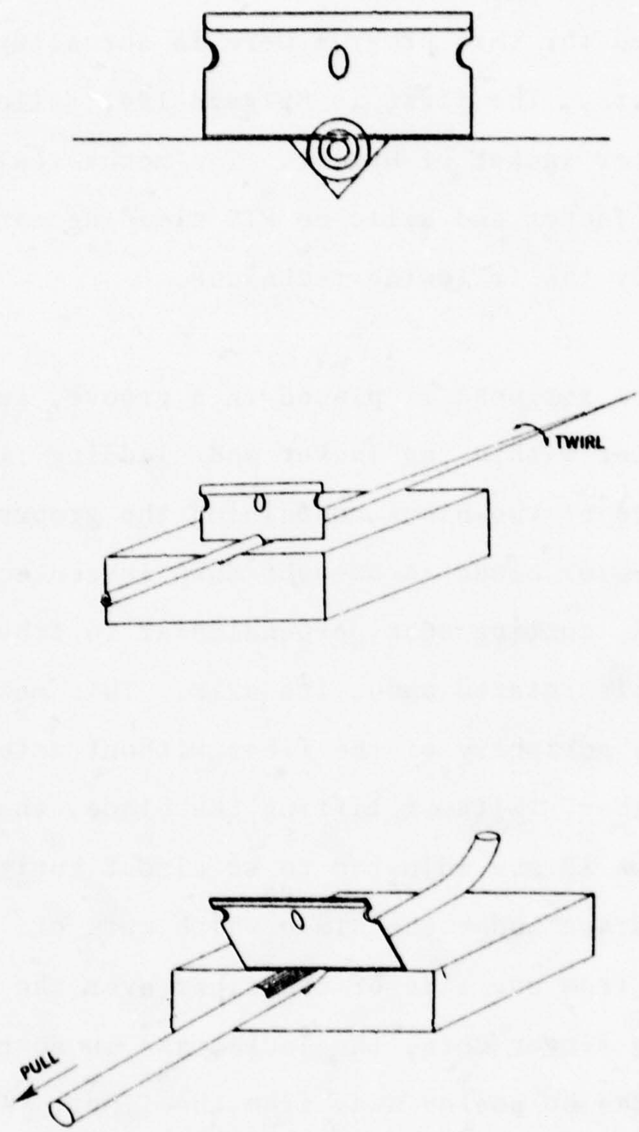

Figure 1. Fiber Jacket Removal.

When preparing fibers for the fabrication of transmission star couplers, the cutting of the Hytrel and silicone jacket is performed at two locations in the center of a length of fiber. A second cut is made at the desired distance from the first cut and the jacket is carefully sliced at the top from the second cut toward the first. The same peeling and solvent cleaning procedures described above completes the preparation of the fiber for use in the fabrication of a transmission star coupler.

4. Methods of Obtaining Intimate Fiber Contact During Fusion

Throughout this program, various techniques were used to hold the fibers in intimate contact for fusion. The first technique, which continued to be used throughout the program, was the use of pure "mercerized" cotton thread. Simply by tying the thread around the fibers using a clove hitch the fibers could be drawn into a close packed structure. In order to maintain this structure, several knots in series were required at each end of the region to be fused to ensure that the fiber would remain parallel and in contact in the region to be fused. It also proved to be of advantage to use a centrally located knot to obtain an extra measure of success. During the fusion process, the centrally located knot would be burned off. With care, but without consistency, the knots could be burned off with little or no remaining residue. Attempts at untying the knots proved to be of no greater reliability, a trade-off between breakage and surface contamination. Other materials were investigated as alternatives to the use of cotton thread. Graphite thread used for cable strength members when heated with the fusion torch evaporated totally leaving no residue; however, the brittleness of this material and the radius of curvature when tied around the fibers precluded its use.

Another material that proved to be useful, although difficult to apply, is polyethylene. Initially, the fibers are held together with thread. The polyethylene was applied to the fibers with a heated soldering iron at several positions along the length of the fibers to be fused and the strings removed from the fibers prior to fusion.

During the fusion process, the polyethylene becomes fluid and recedes ahead of the advancing torch. One must be careful to prevent the fluid polyethylene from wicking down to the jacketed fiber area or removal will be impossible. If the bare fiber forming the coupler is of sufficient length, fusion can occur in the central region without softening the polyethylene or causing the fluid substance from advancing as far as the jacketed fiber region of the coupler. After fusion is complete, the polyethylene is totally removed by igniting it with the torch. The polyethylene burns away leaving no residue.

5. <u>Direct Fusion Considerations</u>

During the early part of the program, experimental fiber fusions were carried out using a propane-oxygen micro-torch. This torch is a handheld unit with individual control of the gas delivery rates, accomplished by needle valve adjustment. The regulation of the flame temperature and profile, using this torch, could only be maintained for short time intervals due to the limited gas supply of the torch tanks, and the resetability of the flame parameters was purely subjective. An improvement in flame parameter control was achieved using a "water welder." This unit, manufactured by "Henes Products Corporation," generates the hydrogen and oxygen by electrolysis. Control of the gas delivery rate is obtained by the adjustment of power supplied to the electrolysis unit with a powerstat (variable transformer).

The use of a pure hydrogen and oxygen flame for fiber fusion was not totally satisfactory. The gas delivery rate necessary to prevent the flame from burning within the torch tip created sufficient flame pressure to distort the coupler during the fusion process. Reduction of flame velocity (combustion rate) and pressure was obtained by bubbling the hydrogen and oxygen gas mixture through methyl alcohol, Figure 2. This resulted in a reduced flame velocity and temperature (3300°C to 2600°C) and a resultant increase in BTU output, which proved to be beneficial in controlling the fusion process.

Dependent upon the physical size of the coupler being fabricated, one of two different torch orifice shapes was used. Circular cross section and a two lobed-flat cross section design (Figure 3) were the preferred cross sections. Orifices of less than .010" diameter were circular and those greater than .010" diameter were the two lobed-flat configuration.

When working on high tap-off directional couplers (smallest device studied), circular cross section orifices ranging from .003" to .005" in diameter were used to produce the fusions. These torch tip sizes were also preferred when performing fiber to fiber butt fusions.

Thirty-two (32) port transmission couplers were the largest items fabricated and a dual torch configuration (Figure 4)

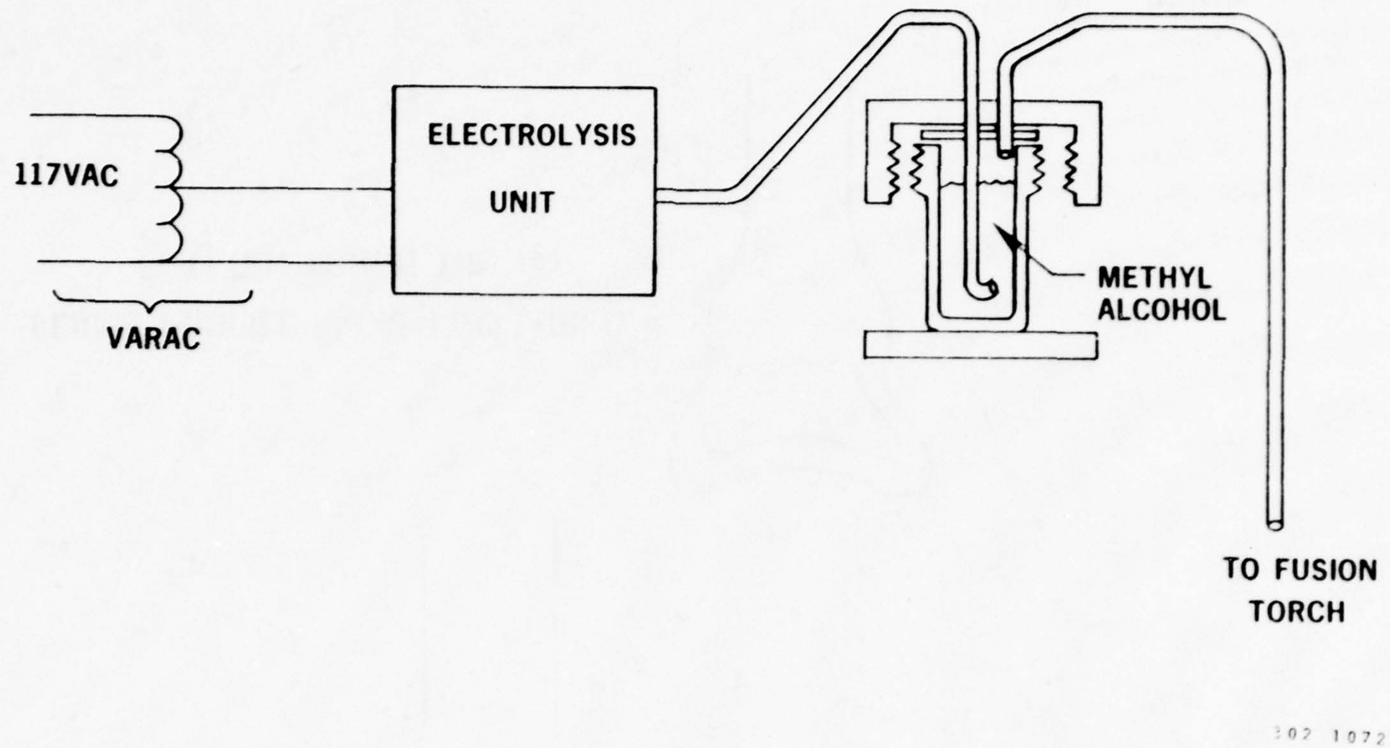

Figure 2. Oxy-Hydrogen Bubbler System.

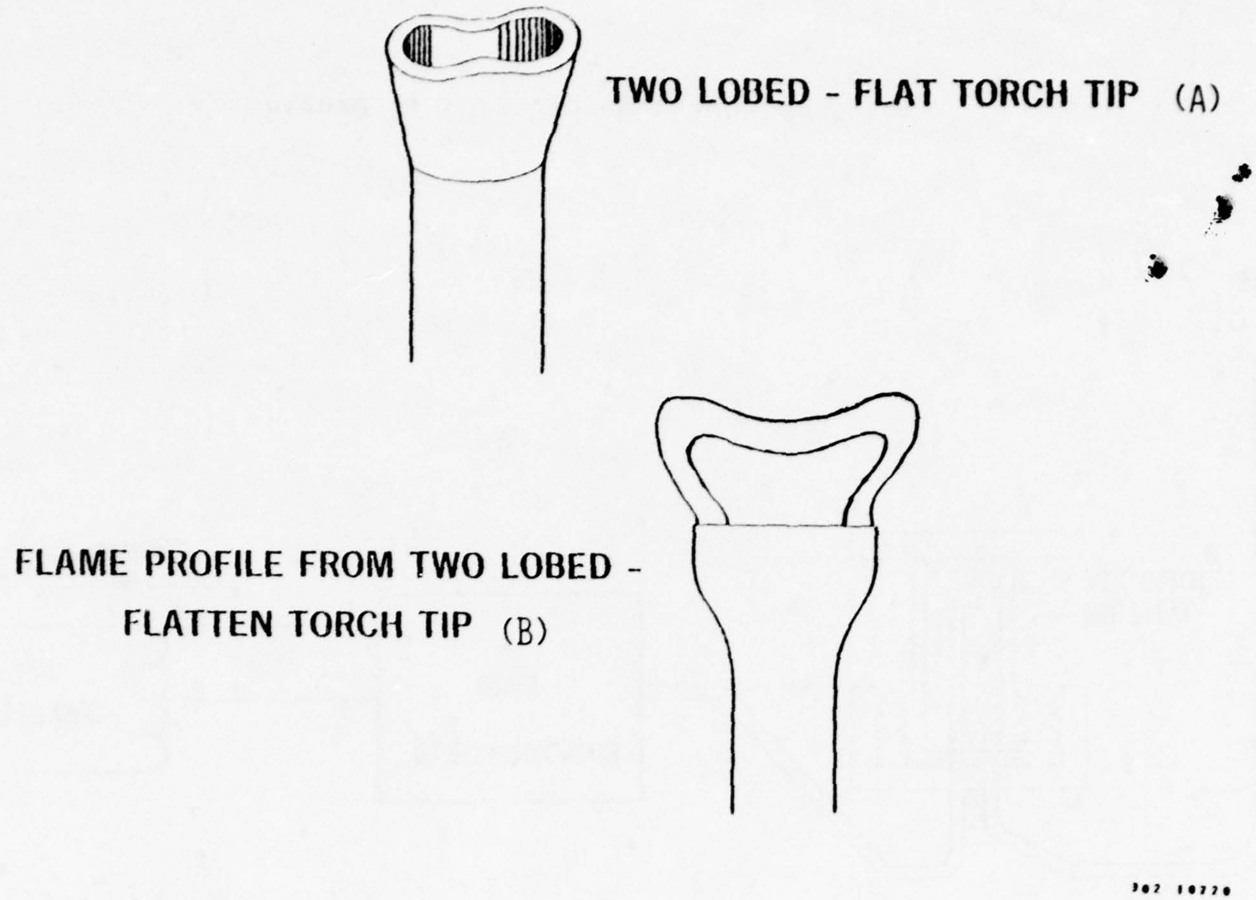

Figure 3. Two-Lobed - Flat-Torch Tip (A), Flame Profile From Two Lobed-Flatten Torch Tip (B).

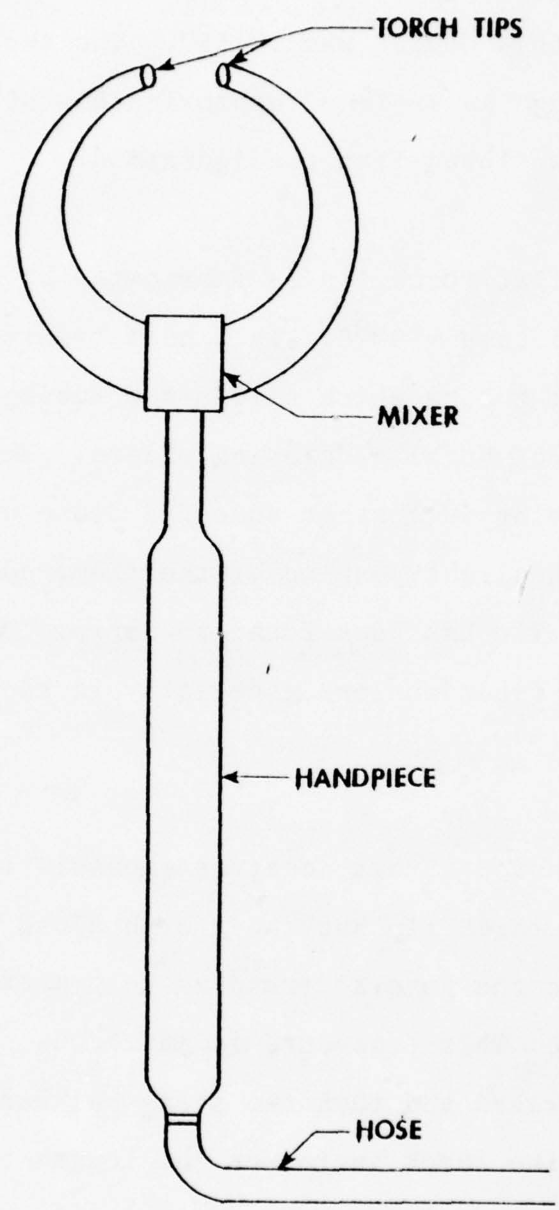

Figure 4. Dual Torch Configuration.

was used to produce the fiber fusions. The preferred orifice size for this device was .0155". The two torches are displaced through an angle of approximately 90^{o}, each tip being of the two lobed-flat configuration.

The two lobed-flat torch tip is fabricated by heating the tip to a cherry red temp $\sim$700^{o}C. This heat treatment softens the stainless steel tubing which allows the tubing to be pressed flat by a pair of parallel closing pliers. The central section of the tubing is further squeezed close until a square flame head with slight peaking of the flame edge is produced. This flame profile has been found to improve upon the uniformity of the fiber fusions especially in the case of the star couplers.

One of the techniques that deserves emphasis is that of "wiggling" the torch tip back and forth along the fibers to be fused, while the general trend is to traverse the fibers with the flame. This procedure is analogous to walking three steps forward and then two steps backward. This "wiggling" of the torch increases the length over which the wetting action and fusion occur and aid in producing smooth transition regions. The amplitude of this "wiggling" may be from one to three millimeters and at a frequency from one to five cycles per second. By varying the proximity of the flame to the coupler, selection of torch tip and operating conditions and the amplitude and frequency of the "wiggling," a wide range of fusion control is achieved.

6. Coupler Cladding Considerations

For a given material to classify as a candidate for use as a cladding, the following properties or set of properties must be met:

1. Cladding material must have a refractive index such that the cladded coupler's numerical aperture is at least equivalent to that of the cladded PCS fibers.
2. Loss contribution, due to the cladding materials scattering properties must be low (<.1 dB additional).
3. The material used should be compatible with the fabrication processes that follow the device cladding.
4. Material should provide some measure of protection to the coupler element from environmental contaminants (dirt and water) and mechanical abuse (vibration and temperature).

Several materials were investigated for use as cladding substances for the couplers developed under this program. Most of the materials investigated were "plastic" in nature, including silicone based RTVs, silicone grease, Nylon® and Kynar®.

Gental 101, a solvent solution of nylon, was found to have too high a refractive index thus failing property #1. Kynar 5200 was investigated as a cladding substance and found to be difficult to use. This material was applied from an acetone solution. Evaporation and consolidation of the coating was obtained using a hot air gun. Due to the quantity of material necessary to coat a coupler, it was difficult to dry the coating without damaging the device.

Although many of the devices fabricated under this program were coated with silicone RTV materials for protection from contamination and vibration, the usefulness of this material as a cladding material is questionable. Drawbacks to this material are 1) very high thermal coefficient of expansion, 2) strong temperature dependence of refractive index and 3) relatively poor mechanical buffering isolation properties. The second and third drawbacks listed are properties resulting from the first.

RTV coated couplers constructed for this program had to be room temperature cured to survive. If cured at elevated temperatures, the RTV would be in an expanded state upon curing and the device would break upon returning to room temperature. Curing of the RTV compounds must be accomplished above $70^{o}C$ for complete cure, or this material will remain tacky.

Toward the end of the program, it was determined that a silicone based Dow Corning high vacuum grease, used for vacuum system seal lubrication, has a refractive index equivalent to that of the RTV materials. Other beneficial properties of this material are: 1) high viscosity, 2) low resiliency, 3) maintains fluid-like nature over wide temperature range allowing the coupler to float within the mass, and 4) serves as a vibration damping medium. The low temperature characteristics remain to be determined.

An additional benefit of using the vacuum grease as a cladding material was the ability to totally remove it, if desired, with solvents. This ability permitted couplers to be measured repeatedly in either a cladded or unclad state. This fact was important also in that it permitted the relative measurement of cladding material performance on the same coupler device.

Cladding materials were also investigated for their potential use on fibers to be terminated in connectors. The use of "plastic" type materials for the termination of fibers in connectors met with a classical set of problems. Poor fiber retention and polishing characteristics were the primary problem areas. The word "plastic" gives insight into the expected problem areas.

Fibers bonded with "plastic" materials such as RTV, polyurethanes, and florinated teflons move in the connector ferrule due to tension on the fiber or even slight movement of the fiber close to the connector. Ambient temperature changes can also cause fiber recession or extension because of the differences existing between the thermal expansion coefficients of the fiber and its Hytrel Jacket. The grinding and polishing of the fiber end faces is also complicated due to the fiber recession caused by processing pressure. When lapping and polishing is complete, the fiber will, with time, advance to its original position displaying a definite overextension characteristic. It is also virtually impossible to obtain a flat polished end face due to the relative softness of the bonding materials. During grinding and polishing, erosion of the bonding material results, and the bonding material becomes loaded with abrasive contaminants.

Because of these considerations, the effort outlined in the next section was required.

7a. <u>Connectorization Considerations</u>

Couplers fabricated from PCS fibers present a special set of problems to the connectorization of these fibers. Standard practice, use of epoxy, for glass clad fiber termination in connectors can not be employed without destroying the waveguiding characteristics of the fibers within the connectors, due to the fact that epoxies, in general, have higher indices of refraction than that of the fiber core material. Attempts to use silicone resins and other plastic materials of lower refractive index have met with failure for the various reasons cited above: 1) poor fiber retention characteristics resulting in movement of the fiber within the connector body; 2) poor polishing characteristics; 3) cold flow of the adhesive material.

The approach taken to solve these problems was that of applying dense metallic, reflective coatings to the fibers such that bonding within the connector can be achieved with standard epoxy adhesives, without significantly affecting the transmission properties of the fiber within the connector.

A procedure was developed for applying silver directly to the fibers by a chemical reduction process. This procedure, a modified Brashear[1] process is used widely by mirror manufacturers, amateur and professional astronomers alike.

The modifications to the basic process are that of using pure, reagent grade materials and fiber cleaning procedures to yield uniform and dense silver films.

In the sections to follow, the fiber preparation procedures, chemical preparation and use procedures are discussed.

7b. Chemical Preparation (Stock Solutions)

The following stock solution can be prepared in stock quantities for multiple uses ($\sim$10 silverings).

[1] Amateur Telescope Making, Book One, Pages 158-159
Albert G. Ingalls, Editor, Scientific American, 1970.

1. Reagent grade potassium hydroxide (KOH) and distilled or de-ionized water (H_2O) 10 gms KOH + 100 ml H_2O.
2. Reagent grade dextrose ($HOCH_2CH(CHOH)_4O$) and distilled or DI water (H_2O) 15 gms dextrose + 150 ml H_2O.
3. Final fiber cleaning solution. Three parts, by volume of KOH stock solution and one part reagent grade ammonium hydroxide (NH_4OH). A total quantity of ~100 ml is usually sufficient for use. Keep tightly stopped when not in use to prevent disassociation of NH_4OH.

7c. Fiber Preparation for Silvering

The techniques described in Section II.2 for removing the jacket and cladding layers result in a distinct jacket/cladding termination plane perpendicular to the axis of the fiber. This method of preparation aids both the subsequent cleaning and silvering operations.

The three (3) step cleaning procedures to follow should be performed just prior to initiation of the silvering procedure to minimize surface contamination. The last step in the cleaning procedure will take place during the final chemical preparation phase prior to silvering.

Step 1 - Squeeze the fiber between folds of a Kimwipe tissue "soaked" with a 50-50 mixture of isopropyl alcohol and Freon TF. Draw the fiber through the tissue. This step should be repeated until the bare fiber appears to remain "wetted" by the solvent solution over the entire length of the bare fiber. A back and forth scrubbing motion near the bare fiber-jacketed fiber area will ensure cleaning of this area.

Step 2 - Submerge the bare fiber and approximately 1/4" to 1/2" of the jacketed fiber in Freon TF and ultrasonically agitate for approximately 15 seconds. Go to Step 3 immediately following this step.

Step 3 - Submerge the fibers in the final fiber cleaning solution described in Section II,7b and ultrasonically agitate for 15 seconds. Leave the fibers submerged in this solution while preparing the chemicals for silver plating.

7d. Final Chemical Preparation and Silver Plating Procedure

It should be noted that the prepared solution resulting from Steps 1 through 4 described below will, if allowed to age, result in the formation of silver fulminate, a potentially explosive substance, and should be prepared just prior to actual use only. Silver fulminate is known to spontaneously detonate at room temperature, however, this process has been used many times at ITT EOPD with no negative consequences.

The total preparation time and plating time involved is approximately ten (10) minutes. After the plating process is complete, the hazards are eliminated by dilution of the solution with water. No environmental problems exist with normal sink disposal.

The following procedures are to be performed on a cold (room temperature) stirring hot plate.

Step 1 - To 50 ml of distilled or de-ionized (DI) water add 2 mg of silver nitrate ($AgNO_3$). Stir until completely dissolved.

Step 2 - Add approximately (if fresh) 2 ml ammonium hydroxide (NH_4OH) to the solution prepared in Step 1 above. The solution will darken at first; add NH_4OH slowly until solution clears. If the NH_4OH has weakened slightly through disassociation, slightly greater quantities are required.

Step 3 - Slowly add 10 ml of potassium hydroxide (KOH) stock solution. Solution will again darken.

Step 4 - This step should be carried out slowly due to the fact that the precipitate formed in Step 3, which is responsible for the darkening of the solution, is not to be completely redissolved in this step. Add small quantities of ammonium hydroxide (NH_4OH) and stir for approximately one minute before more is added. The total quantity required is approximately 1 ml if NH_4OH is fresh and some color (weak tea) should remain to the solution.

Step 5 - To 50 ml of distilled or DI water, add 15 mL of stock dextrose solution.

The plating process is now ready to start.

The container holding the solution from Step 4 should now be placed in an ultrasonic cleaner with light to moderate coupling to the sonic power. Remove the fibers from the final cleaning solution. Pour the dextrose solution into the container holding the silver nitrate preparation and submerge the fibers to be plated. Plating is completed within three (3) minutes.

Rinse the fibers with running DI water for approximately 15 seconds. A second rinse is then applied by squirting or submerging in isopropyl alcohol to dry the film.

If the fiber cleaning procedures were performed adequately, the silver coating should be continuous not only on the bare fibers but also on the jacket material.

If multiple fibers are to be processed simultaneously, care should be taken to prevent direct contact during the plating process or voids may exist due to masking.

7e. Application of Connector to Silvered Fiber

The finite reflection coefficient of the silver coating places a practical limit upon the length of fiber that can be used within a connector ferrule without introducing significant additional loss. Although the reflection coefficient appears to be $\underset{\sim}{\sim}$98%, only three (3) reflections will contribute ∿0.25 dB loss. For a fiber of .005" (127 μ) diameter, with an NA of ∿.33, a length of silvered fiber of approximately 1.0 mm will result in ∿3 reflection lengths.

Some additional precautions are advised when bonding the silvered fiber within the ferrule. At the silvered fiber/cladding interface, mechanical stress or temperature variations during the epoxy curing cycle could cause unsilvered fiber to protrude slightly beyond the cladding region. If this occurs and contact is made between the fiber and epoxy, high losses will result due to relatively high refractive index of epoxy, with respect to the silica fiber, destroying the waveguiding properties in that region. The application of a small quantity of silicone grease in this area serves to prevent this phenomenon.

In order to control the total length of silvered fiber within the connector, a mechanical stop, a length of stainless steel tubing is bonded to the fiber jacket such that the front end of the tube extends just beyond the silvered fiber/cladding interface by $\sim$1/2 mm, and is inserted into the connector until the tube seats against the back of the jewel. Figure 5 illustrates the fiber in ferrule sectional view.

After epoxy curing is complete, normal lapping and polishing procedures complete the connector installation task.

8. Characterization of Coupler Components

In the early stages of the program, the measurements performed on the couplers were conducted at 0.79 μm wavelength. These initial measurements were also made over a range of injection numerical aperture from .089 to .336. To varying degrees, all devices exhibited higher excess loss at the

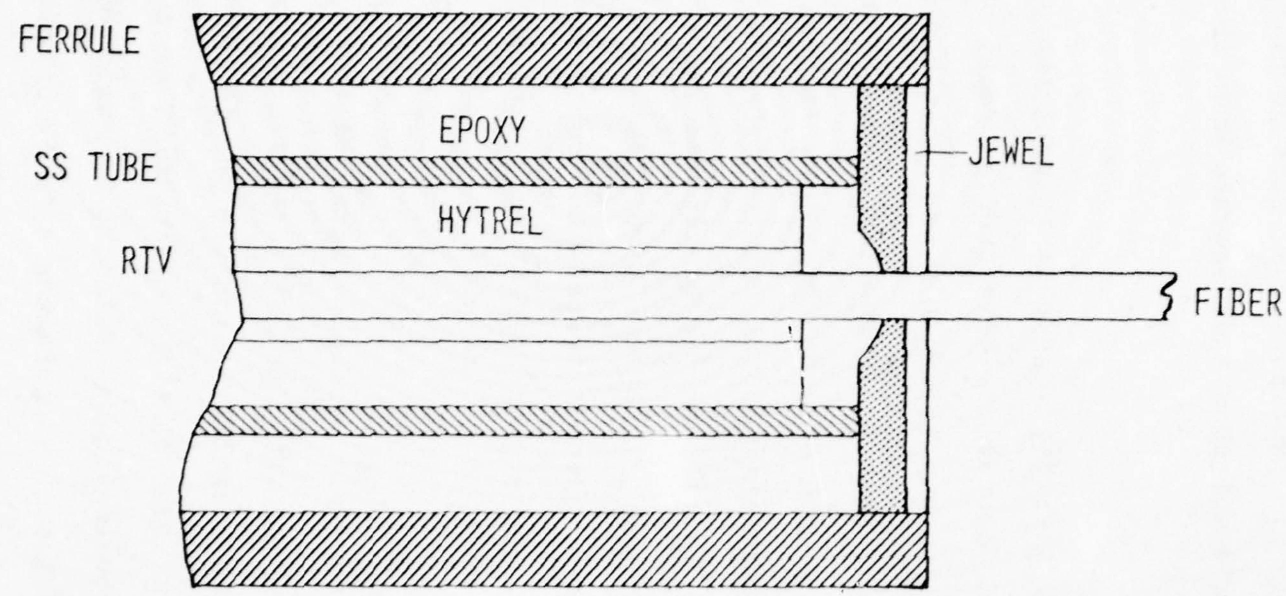

Figure 5. Section View of Fiber in Ferrule.

high injection N.A.'s. The individual port coupling coefficients, however, did not show a dependence upon the injection N.A.

The method used to ascertain the port-to-port throughput loss for the couplers developed for this program requires that the input fiber injection conditions are not disturbed during the measurement period. With this requirement met, the power that is available at any one, or a set of ports, is measured and recorded. The input fiber is now cut approximately one meter from the injection point, the end is cleaved and the injected power level is measured. Couplers of pigtail construction are usually fabricated with approximately two or three meters of fiber pigtail for each port to allow for additional measurement cycles.

As the number of couplers produced increased, the measurement complexity was reduced such that all devices were characterized under full modal excitation only. The injection apparatus was constructed such that two measurement wavelengths were available. The wavelength was selected by switching the drive current to one of two LEDs operating at 0.82 μm and 1.06 μm respectively. The optical power from these sources is brought to a common optical interface point by the use of an even split directional coupler used as an optical power combiner.

Figures 6 and 7 illustrate these apparatuses. The 1.06 μm source, a Ga1-103, etched well device was obtained from the United Kingdom as part of the technical cooperation program, JPT-10. Excellent correlation is obtained by measurements obtained by the two measurement systems.

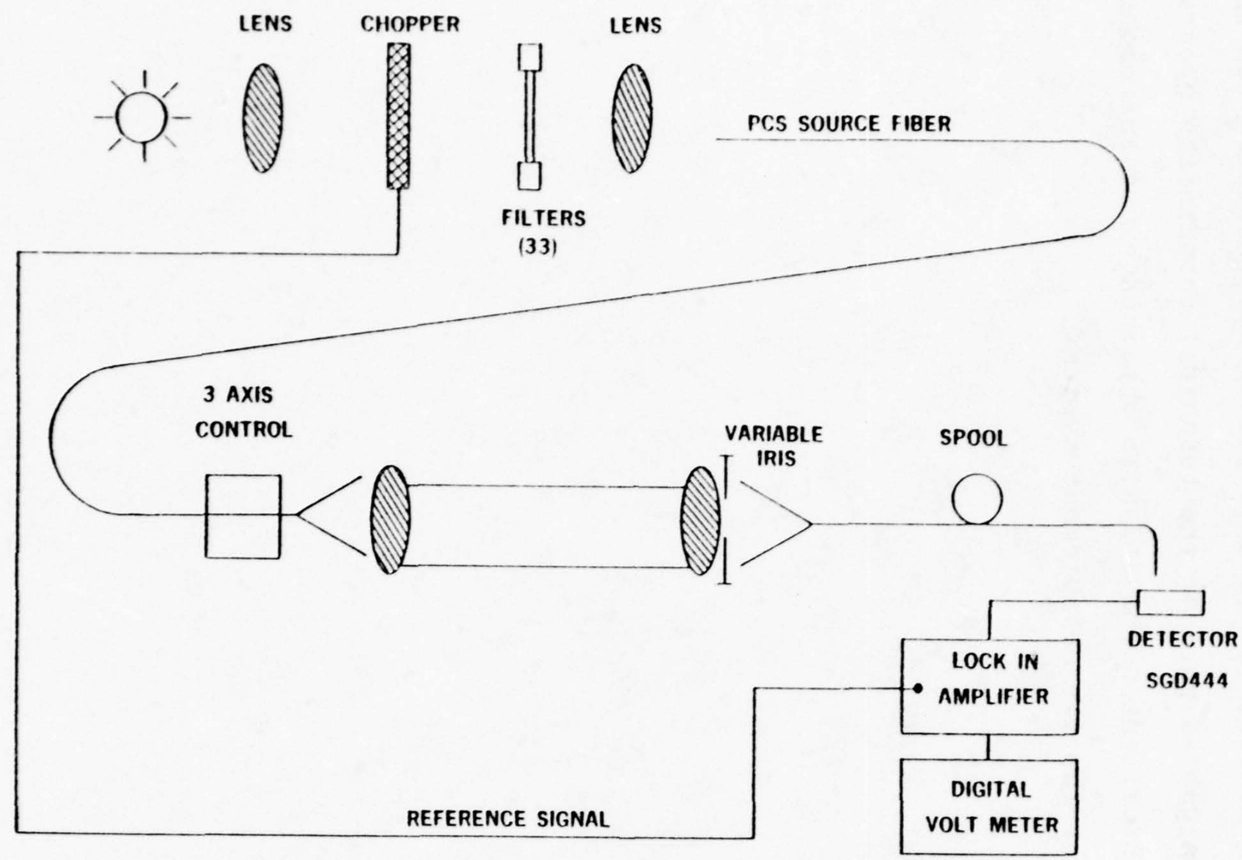

Figure 6. Attenuation Measuring Equipment.

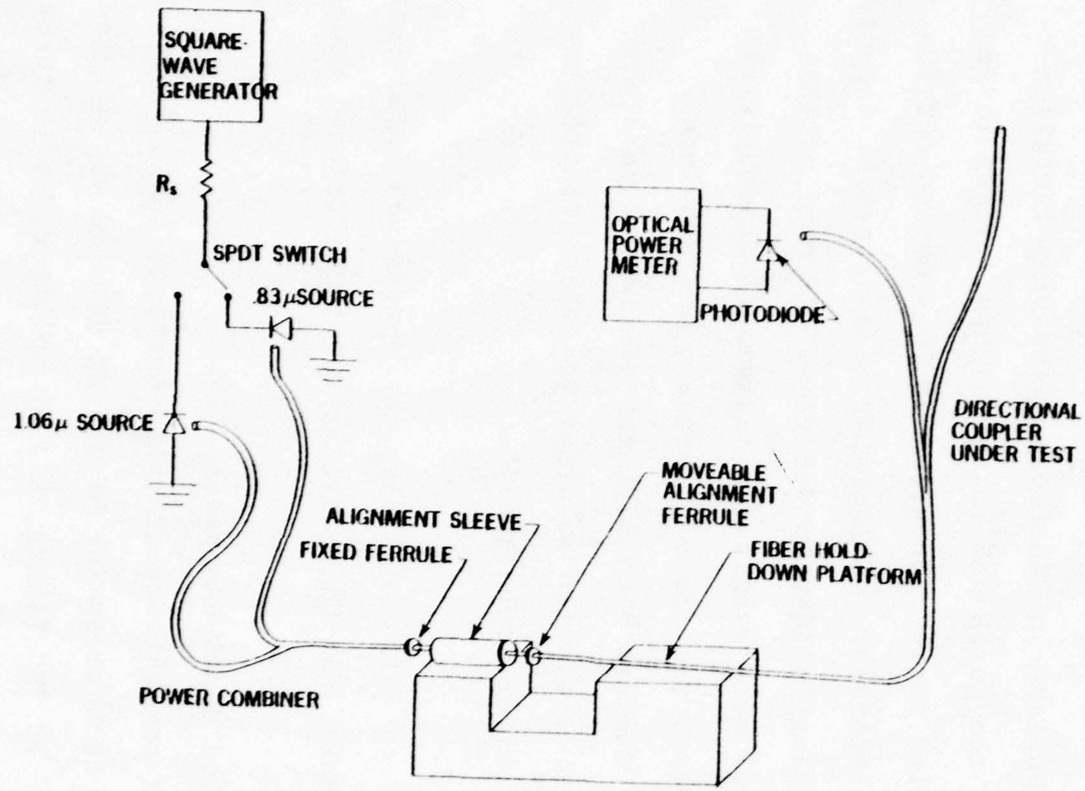

Figure 7. Multiwavelength Measurement Station.

SECTION III

DIRECTIONAL COUPLERS

The goals of this task were to develop techniques to form three-port couplers in PCS fibers providing isolation between two of the ports and low throughput excess losses between coupled ports. Couplers of this design can function as power splitters or combiners or as monitors or tap-off devices sampling incident power flow. As part of this exploratory effort, even split designs (3 dB couplers) were fabricated, techniques improved, and couplers evaluated. Couplers with high tap-off ratios were also fabricated and evaluated in order to assess limitations due to fabrication techniques.

The sections to follow describe the approaches investigated, chronologically, for the fabrication of directional couplers.

1. Bifurcated Bundle Approach

The original concept investigated borrowed ideas from standard bundle technology for producing desired tap-off levels. For a bundle of "N" fibers, a 3 dB splitter can in theory be formed simply by bifurcating the bundle into two N/2 fiber groups. Higher tap-off ratio devices are obtained by selecting a smaller quantity than half of the total number of fibers for the tap-off port. See Figure 8.

The fiber size chosen for use in the bundle would be such that the sum of the individual fiber cross-sectional areas would closely match that of the port of primary concern. Fusion of the fibers into a single cross section would, at least in theory, minimize losses if the average modal power density and volume is maintained. In order to achieve this result, mode conversion, that is conversion from propagation to radiation modes, must be kept to an absolute minimum.

Devices were fabricated in the early part of the program from as many as nine (9), 50 μm fibers. Many problems existed with this approach. The RTV cladding used on this fiber could only be removed completely by chemical methods. The fibers were so small that handling them when uncladded was extremely difficult. Measurement was also extremely difficult and the results were very erratic. These problems and others caused a modification to the techniques used to evaluate the bundling approach to coupler fabrication.

Devices of the bundle type were fabricated using 127 and 203 μm fibers, in order to evaluate the approach. Table 1 shows the levels of excess loss obtained as function of the

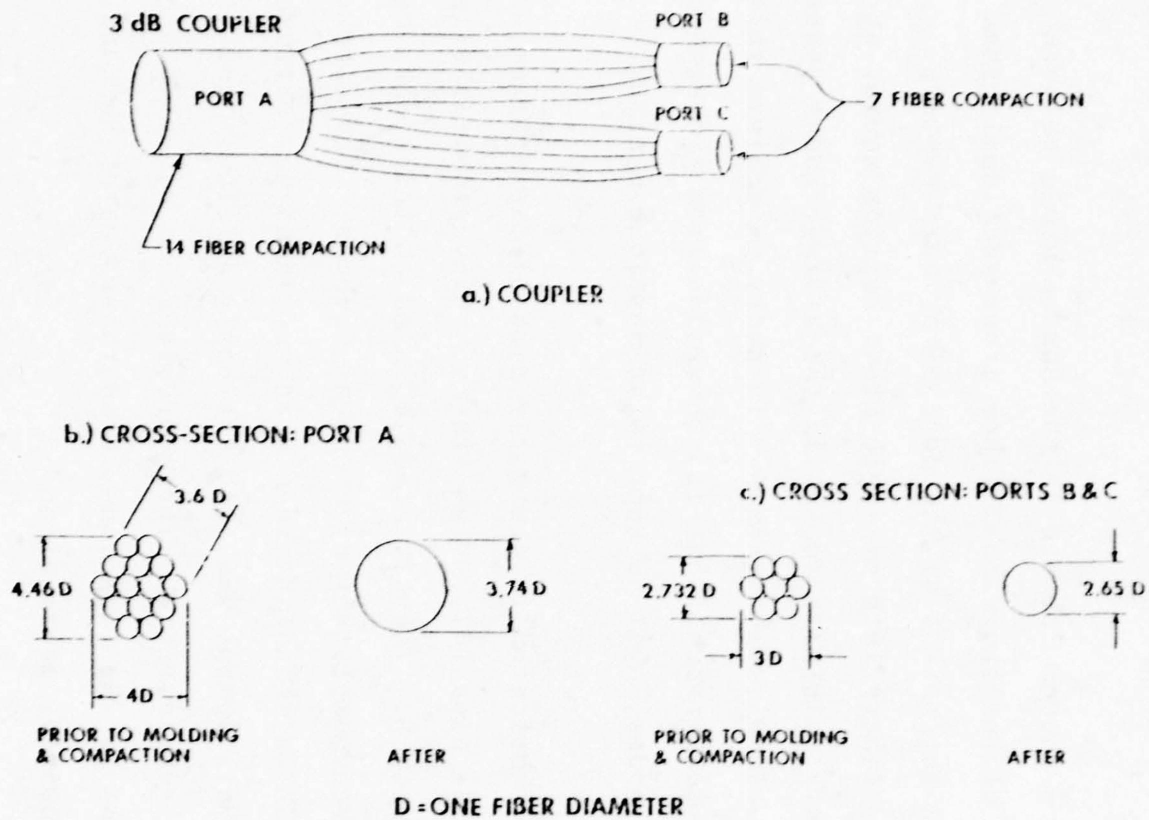

Figure 8. 3 dB Directional Coupler.

Table 1. Excess Loss vs Number of Coupler Fibers.

Device #	# Fibers	Fiber Dia.	Excess Loss dB
005	2	.008"	-.6
002	3	.005"	-1.8
001	4	.005"	-3.7
009	7	.005"	-3.3

number of fibers used to fabricate the design. Not only does the excess loss have some dependence on number of fibers, but one can also expect loss to be introduced by the fusion of the bifurcated arms. Clearly, a different approach requiring small numbers of fibers to fabricate a coupler and which keeps the constituent fiber sizes within reasonable handling ability was called for.

2. Two Fiber Approach

In this approach, the coupler is formed by the fusion of two parallel fibers. The two fibers are fused and caused to transition gradually to a circular cross section to mate with a single fiber. A nominal 3 dB coupler is formed when the two fibers that are fused together are of equivalent diameters. Other tap-off ratios are obtained by adjustment of the diameter ratios between the two fibers forming the coupler.

Table 2 indicates required fiber sizes for constructing couplers of a desired tap-off level.

3. Directional Coupler Fabrication

The construction guidelines for the devices for this task were in part set by measurement requirements. The fused and compacted cylindrical portion of the couplers were butt

Table 2. Side Arm Coupling Ratio vs Constituent Fiber Size.

Side Arm Coupling Ratio (db)	Side Arm D_1 (um)	Throughput Arm D_2 (um)	Input Arm D_3 (um)
-3	88.4	88.4	125
-4.4	75	100	125
-5.50	125	200	235.9
-6.0	100	173.1	200
-6.0	125.3	216.3	250
-8.6	50	125	134.6
-10	40	120	126.5
-12	50	200	206.2

fused to fibers of similar cross-sectional area. This allows measurement of the injected power by cutting the injected port fiber to measure the input power level.

The requirement for the butt fused fiber length necessitated fixturing to permit scribing and breaking of the fused coupler to attain clean, perpendicular end faces for the subsequent butt fusion. The fixturing arrangement resembles that used to perform fusion splices, the primary components being a fixed fiber holddown plate and a micromanipulated plate for alignment.

In the even split (3 dB) directional coupler design, the fibers to be fused to form the main body of the coupler would be typically several meters in length to allow for several measurement cycles. One end of these fibers would be stripped of their jacket and cladding over approximately six (6) inches in length, and thoroughly cleaned with solvents. The jacketed portion of the fibers nearest the stripped fibers are tied together and the hytrel jackets melted together using a hot air gun. This fusion of the fiber jackets has two benefits: 1) as the jackets melt, the thickness of the intervening hytrel is reduced, thus decreasing the fiber to fiber spacing and congruence angle to the fused region; 2) as the fibers are now held fixed with relationship to one another, the possibility of twisting the fibers independently is eliminated. This technique aids in producing consistently better devices due to minimization of physical distortions.

At this point, the fiber pair is taped to the stationary plate of the fusion fixture with the hytrel jacket overhanging the edge of the plate by approximately one-half inch. The distance between the stationary and micromanipulated plates should be on the order of three inches.

The fibers are now drawn together with a clove hitch using pure cotton thread. The clove hitch prevents twisting during tightening due to the inherent inline loop configuration of this knot. Figure 9 illustrates the clove hitch knot tying procedure with and without half hitch termination.

The clove hitch is drawn tight and secured on the loop side of the knot with a half hitch. The knots should be applied near the jacketed fiber end and slid down the fibers toward the end of the bare fiber. This technique removes slack in the fibers and ensures intimate fiber contact. Two knots spaced approximately 1/8" should be used at each end of the bared fiber. The fibers at the end of the coupler are now taped to the plate at the other end of the fixture and molten polyethylene applied for approximately an inch over the

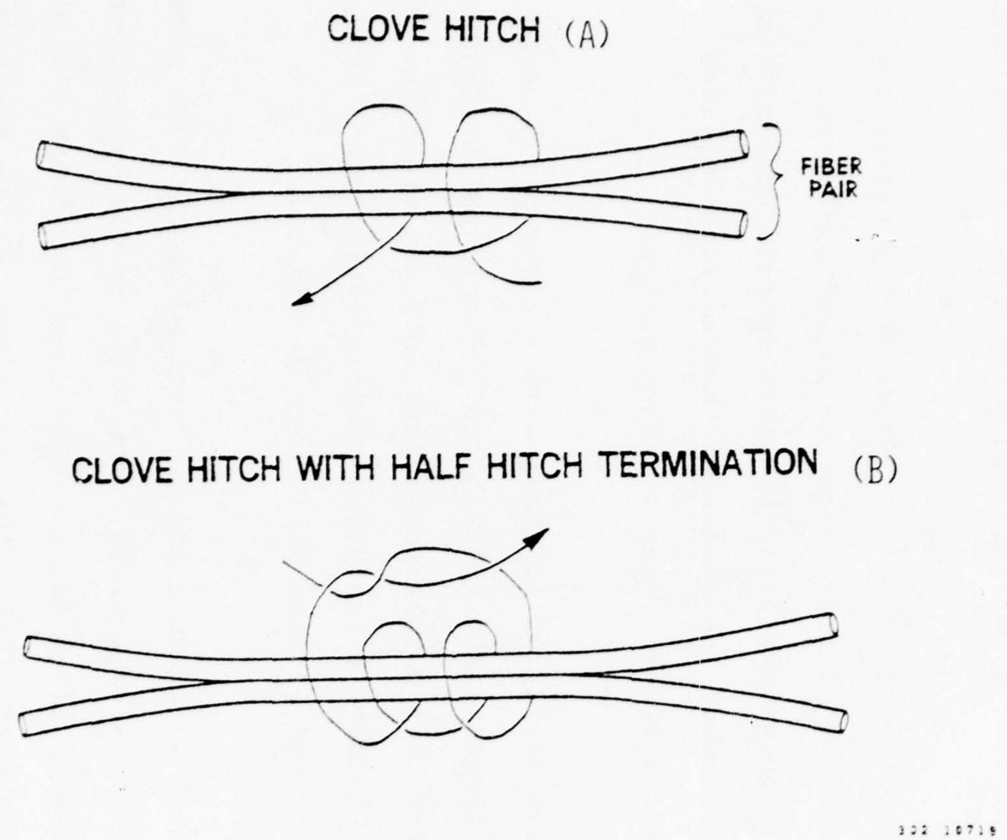

Figure 9. Clove Hitch (A), Clove Hitch With Half Hitch Termination (B).

central region using a hot soldering iron for application. The fusion process is now initiated between the knots and polyethylene coated region of the fibers at the end away from the jackets. The fusion process is continued down the length of the fibers toward the jacketed fibers until a straight section of circular cross section is obtained with a smooth transition region.

With the fusion process complete, the coupler is held by tweezers (or otherwise clamped) and scribed in an area of circular cross section. The downstream end of the coupler, that mounted on the micro-manipulated plate, is discarded. A fiber of equivalent cross section to that of the fused coupler is now taped to this plate, with 1/2" of jacket overhang, in preparation for the butt fusion process.

The fiber to be butt fused is now adjusted for perfect axial alignment between it and the coupler. The fibers are brought in close proximity and heated using the smallest flame possible. As the end faces bulge and contact, the single fiber is advanced slightly to maintain a constant cross section. The torch is manipulated around the periphery of the fibers to ensure uniform wetting of the joint area.

Upon completion of the butt fusion, the coupler is ready for removal from the fusion apparatus. Epoxy is applied to a microscope slide (75 mm) to the areas of the slide where the jacketed fibers will lie. The slide is brought into contact with the fibers. If necessary, additional epoxy may be applied with care taken to prevent application to the bare fibers. Upon curing, the tape holding the fibers to the alignment plates is removed and the device is ready for measurement.

The performance of a specific coupler can usually be inferred from the physical appearance of the coupler. Devices with straight and gradual transition regions have yielded the lowest losses, but cleanliness is also extremely important.

4. High Tap-Off Directional Couplers

The smallest PCS fiber obtained internally for this program has been 30 μm in diameter. This fiber, used in conjunction with a nominally .005" (127 μm) fiber, produced a coupler of approximately 12.7 dB tap-off from the power entering Port #1. For these couplers, it was not necessary to perform a butt fusion for measurement purposes.

In fabricating these couplers the central portion of a fiber (127 μm) is stripped of its jacket and cladding, and the bare end of a 30 μm fiber is fused to the 127 μm fiber. Care must be exercised to ensure that the intermediate stripped fiber region remains straight to prevent mode conversion. The fiber fusion process itself is also different from that used for the 3 dB design. The flame pressure of the torch will easily blow the 30 μm fiber from intimate contact with the larger fiber. To prevent this, the 30 μm fiber is heated primarily by conduction from the larger fiber. This operation is somewhat analogous to reflow soldering. The small fiber is shielded from the torch flame by the larger fiber, thus preventing movement during fusion.

5. Directional Coupler Characterization

Figure 10 is a graphical representation of directional coupler performance with all modes excited in both the unclad (unrestricted coupler N. A.) and cladded (coupler NA = fiber N. A.) states. In all cases, within measurement accuracy, the excess loss was greater for the cladded coupler state. Those devices which lie on or about the "mode conversion independent attenuation profile," most likely suffer from problems relating to cleanliness. Devices far removed from this line indicate substantial mode conversion.

To understand this process, consider that mode conversion occurs at the transition regions into and out of the coupler.

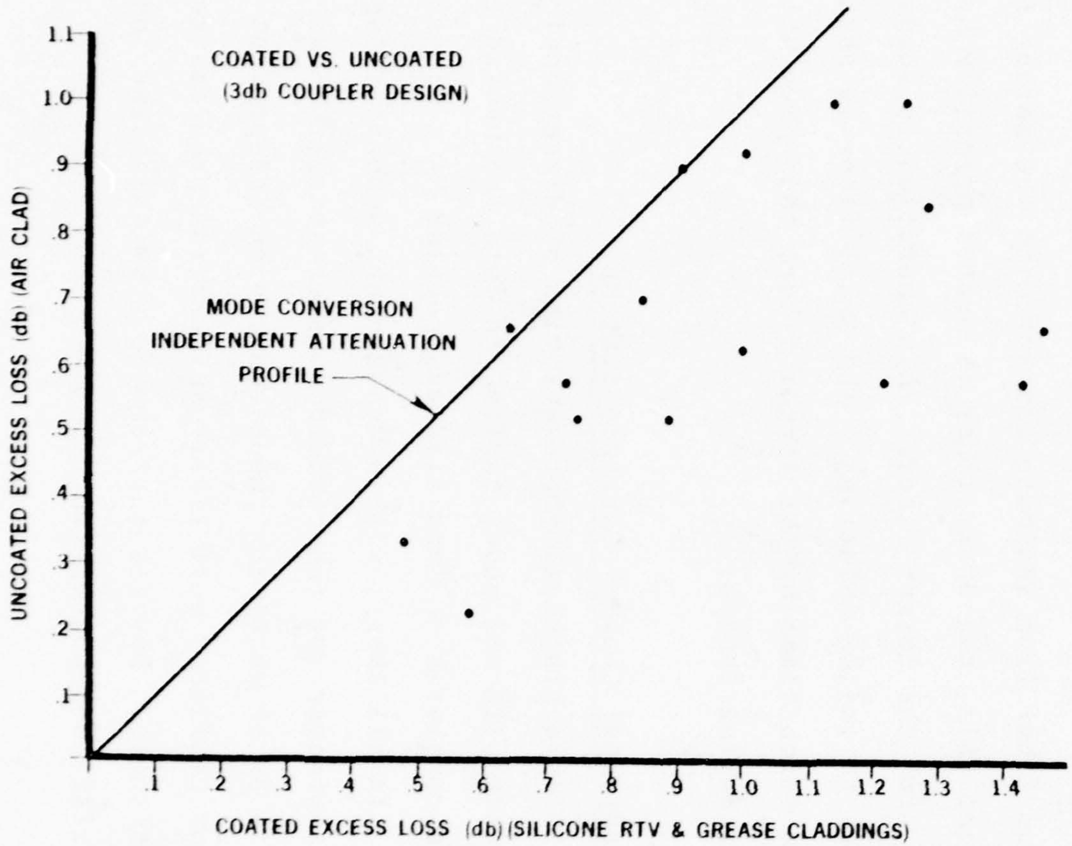

Figure 10. Directional Coupler Excess Loss.

In the uncladded state the numerical aperture of the central coupler region is very large, so that even with conversion to very high order modes, this energy remains trapped in the core material. Some of the very high order modes may then be reconverted so as to be within the numerical aperture of the output fibers. With the application of cladding material to the central coupler region the energy residing in the higher order modes is removed from the coupler and is no longer available to be down-converted into propagating modes of the output fibers.

More than 150 directional couplers of the even split design were fabricated during this program. Of this total, 81 were characterized. The average excess loss for these is -1.32 dB uncladded. In the cladded state, -1.41 dB excess loss was the average.

Table 3 indicates the best results obtained to date for directional couplers of the 3 dB design. For the high tap-off variety of directional coupler (highest tap-off produced only), 22 were characterized in the uncladded state. Due to the fiber diameter variations existing in the constituent fibers used to fabricate these coupler types, design tap-off levels could be expected to vary from -11.95 dB to -14.20 dB. These tap-off

Table 3. Data for Even-Split Directional Couplers.

All Measurements Done with Full NA Injection

Device #	Cladding	λ(μm)	Port 1 (dB)	Port 2 (dB)	Excess Loss (dB)
880	Air	.83	-3.31	-3.16	- .22
	Sylgard 184	.83	-3.59	-3.59	- .58
928	Air	1.06	-3.50	-3.71	- .59
	High Vacuum Grease	1.06	-3.72	-3.74	- .72
940	Air	1.06	-3.38	-3.70	- .52
	High Vacuum Grease	1.06	-3.89	-3.89	- .88
	High Vacuum Grease	.83	-3.03	-3.51	- .26
959	Air	1.06	-3.44	-3.63	- .52
	High Vacuum Grease	.83	-3.74	-3.75	- .74
966	Air	1.06	-3.83	-3.88	- .84
	Air	.83	-3.60	-3.82	- .70
	High Vacuum Grease	.83	-4.25	-4.41	-1.33
967	Air	1.06	-3.58	-3.83	- .70
	High Vacuum Grease	1.06	-3.73	-3.98	- .84

levels translate to -0.29 dB and -0.17 dB total throughput loss respectively. The uncladded performance data for this sample is -1.85 dB average throughput loss. The actual tap-off levels obtained were -16.34 dB average, with a standard deviation of 1.64 dB. Total excess loss was -1.56 dB average. Six (6) of the lowest loss, high tap-off devices were measured in the cladded state as well. Their performance was as follows:

Throughput loss: -.98 dB, σ = 0.17 dB

Tap-off level: -15.58 dB, σ = 0.43 dB

Total excess loss: -0.84 dB, σ = 0.16 dB

The results obtained for these couplers appear in Table 4.

6. Directional Coupler Conclusions

Further technique development, fixturing and device packaging improvements are expected to yield devices with consistently less than 0.7 dB excess loss. Based on the results of this program, 0.3 dB excess may ultimately be achievable. This conclusion is based on a number of factors that relate to the results obtained from this program. The configuration of the devices made control of the fabrication processes difficult. This is to some degree responsible for the excess loss levels obtained and certainly responsible for the variation existing from device to device.

Table 4. Data for High Tap-Off Directional Couplers.

ALL MEASUREMENTS DONE WITH FULL N. A. INJECTION

DEVICE #	CLADDING	λ (μm)	PORT (dB)	TAP-OFF (dB)	EXCESS (dB)
903	AIR	.83	- .89	-14.15	- .69
	SYLGARD 184	.83	- 1.13	-15.20	- .96
858	SYLGARD 184	.83	- .88	-16.11	- .75

Figure 10 is representative of the performance spread obtained for the 3 dB couplers fabricated during the latter portion of this program. More than half of these devices, when coated, had excess loss less than 1.0 dB. Two of the devices plotted had excess loss less than 0.60 dB when coated, and in the uncoated state, less than 0.35 dB. With suitable modification to the fusion fixturing, improvements in the fusion technique and the use of a packaging concept that prevents or minimizes distortion of the couplers, improved performance will result.

SECTION IV
"T" COUPLERS

A "T" coupler, as defined for this program, is a device that distributes the power incident at any one of the ports to the remaining ports in a proportion predetermined by the device construction details. The devices investigated and reported on here are of two types - an even splitting coupler, that is, the power incident on any port is divided evenly between the remaining two ports independent of the port selected for the input, and a high tap-off coupler. The operation of the high tap-off design is best illustrated by example.

Assume that a system exists whereby information exchange (power flow) takes place in both directions over the transmission line, and it is desired to monitor the information flow in both directions along the transmission line without significantly altering the strength of the signal. A high tap-off "T" coupler will fulfill these requirements.

By examination of the schematic representation of the "T" couplers, Figure 11, it is noted that each of the arms or ports of the device are, in essence, directional couplers. The directional coupler at the input arm serves as a power

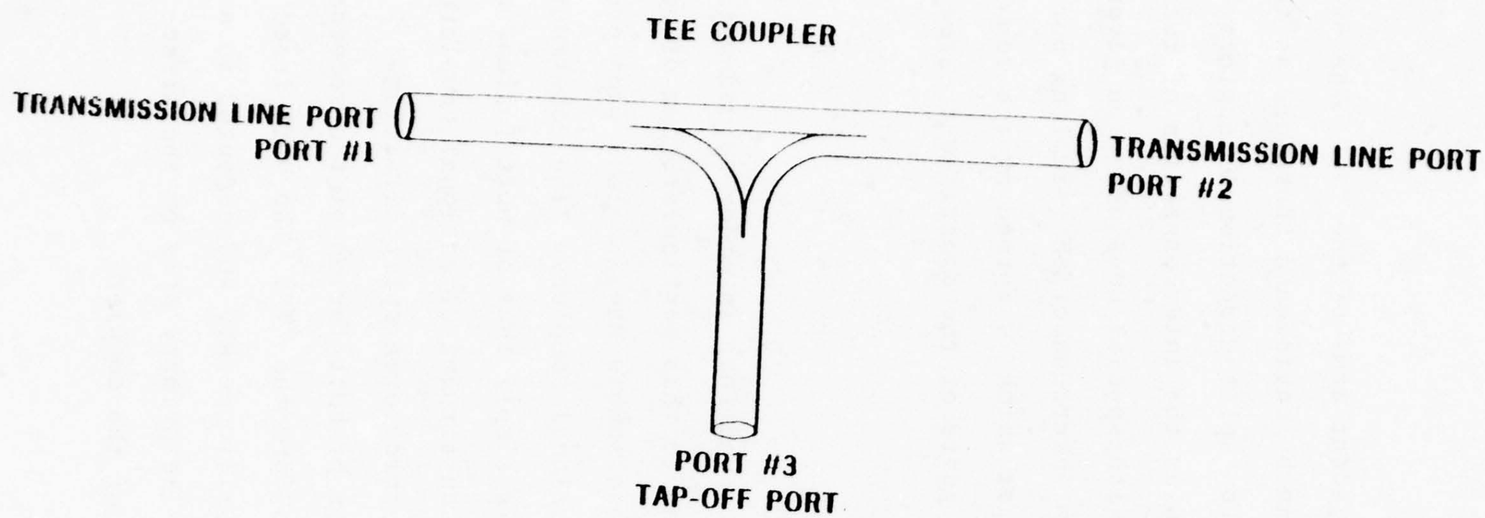

Figure 11. "T" Coupler Configuration.

splitter to each of the adjacent arms of the "T." The even split "T" coupler design can be envisioned therefore as the interconnection of three even split directional couplers, and the high tap-off design as the interconnection of two high tap-off directionals with special consideration given to the sampling port system interconnection (sampling port or peripheral port being that which is formed by the combination of the high tap-off ports of the constituent directional couplers).

1. "T" Coupler Fabrication

During the program, it was found that in order to understand the loss mechanisms inherent to this particular form of optical coupler that it was best to assemble the couplers from previously characterized directional couplers. The construction details for these devices is simply that of butt fusions of the secondary arms of the constituent directional couplers. For the even split design, three even split directional couplers are joined together by butt fusion of the secondary arms of the directionals to form the "T". The butt fused joints were recladded with silicone RTV and cemented to a substrate for protection. The primary arms of the directionals now form the ports of the coupler.

In the high tap-off "T" design, only two high tap-off directional couplers are required to form the device. The larger secondary ports are butt fused to form the main internal throughput arm of the coupler. The two smaller fibers of the directionals are fused together and to a 127 μm fiber to form the peripheral output port arm.

2. "T" Coupler Performance

Table 5 illustrates the results obtained for "T" couplers of the 3 dB design. Figure 12 depicts the results of one of these devices in terms of the "T"'s performance and the individual performance of the constituent directional couplers.

As seen in Figure 12, the total throughput loss, from any port, to any other port was greater than the sum of the losses associated with the directional couplers involved in the particular path and direction examined. This problem was in evidence in all of the even split "T" couplers fabricated as part of this effort to varying degrees.

There is strong evidence that the source of the additional loss in the even split "T" couplers is modal-power-redistribution that is present in the individual directional couplers. Because the total power division in the

Table 5. Even Split "T" Couplers.

"T" - 881/883/895

Injected Port #	Coupling Ratio (dB) Detected Port #			Excess Loss (dB)
	881	883	895	
881	--	-7.47	-7.35	-4.40
883	-8.17	--	-7.38	-4.74
895	-5.37	-7.43	--	-2.43

Injected Port #	Coupling Ratio (dB) Detected Port #			Excess Loss (dB)
	861	879	893	
861	--	-8.67	-8.08	-4.94
879	-8.06	--	8.22	-4.71
893	-8.43	-7.72	--	-4.63

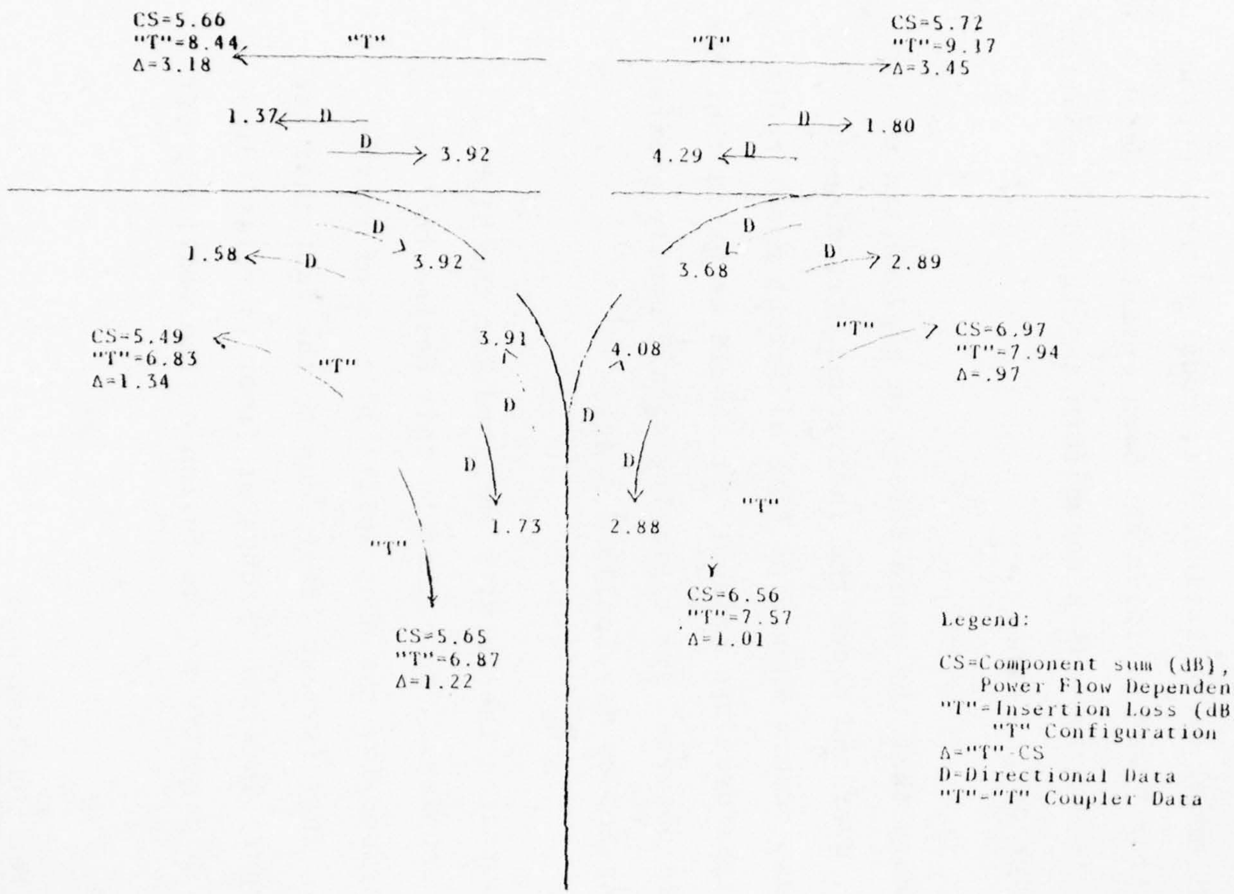

Figure 12. "T" Coupler Performance Data.

directional couplers appears to be essentially independent of the input modal distribution, this modal redistribution must come after power division has been essentially established. It is observed as a nonuniform angular distribution in the coupler output arms.

It thus appears that the extra losses in a given arm of a "T" coupler, over and above the individual directional excess losses, occurs when arms with different modal redistribution signatures are joined. It should be noted that the excess losses observed are typically significantly greater than splicing losses (typically 0.3 dB).

Table 6 illustrates the results obtained for the high tap-off "T" couplers. Note that in this design the problem described for the even split "T"'s is of little consequence. This is most likely due to the fact that the primary (larger) internal throughput fiber is relatively undisturbed in geometry by the fusion of the small tap-off fibers.

3. "T" Coupler Conclusions

The excess loss levels exhibited by the "T" coupler of the even split design was greater than originally anticipated.

Table 6. Data for High Tap-off "T" Couplers.

"T" Coupler 975/979

Port #	Cladding	λ	Throughput Port (dB)	Tap-Off Port (dB)	Excess Loss (dB)
975	Dow Corning High Vacuum Grease	.83	- 1.50	-25.18	- 1.48
979			- 2.95	-22.52	- 2.90

"T" Coupler 974/978

Port #	Cladding	λ	Throughput Port (dB)	Tap-Off Port (dB)	Excess Loss (dB)
974	Dow Corning High Vacuum Grease	.83	- 1.21	-16.03	- 1.07
978			- 1.04	-15.65	- .90

In addition, the method of fabricating the "T" couplers from individual directional coupler elements leads to a configuration that is not amenable to packaging for real system implementation. However, the results reported here do indicate that controlled fusion processes are a viable approach to fabricating these devices.

It appears that to improve coupler performance the source of modal redistribution must be identified and significantly reduced. On the basis of visual observation of coupler physical characteristics, it appears that the modal redistribution problem is geometry related.

To reduce the geometric variation existing in the transition regions from device to device and the influence of externally induced strains that are responsible for this variation, new fabrication processes and packaging concepts are required. Fabrication of the couplers from short lengths of fibers in a fixture such that they are in a totally relaxed state during fusion is expected to achieve a greater degree of control over the geometry of the transition regions.

In consideration of the overall package design for "T"'s, it is also important to consider a design that will allow the device, as fused, to remain uncladded in order to further minimize loss due to the limiting of the coupler's numerical aperture. The packaging design concept should also provide for a method of coupler interfacing to the outside world by way of an integral connector. The approach eliminates the introduction of externally induced stress, a potential cause of device failure. Additionally, the package design must be capable of protecting and preserving the coupler from the extremes of the operating environment.

SECTION V

STAR COUPLERS

The goals of this task were to develop fabrication techniques for transmissive and reflective star couplers utilizing the direct fusion approach as a primary technique. Seven (7), nineteen (19), and thirty-two (32) port devices were to be investigated.

1a. Transmission Star Coupler Fabrication

The fabrication processes described in Section II of this report are a general set of fabrication procedures applicable to all of the coupler forms investigated during this program. There are, however, a special set of fabrication considerations and procedures that pertain to the transmission star couplers. These considerations are described in the paragraphs that follow. Two of the transmission star couplers investigated were fabricated with the correct number of fibers that form a hexagonal close-packed structure (7 fiber and 19 fiber groups). For these devices, the use of cotton thread to draw the fibers together for fusion works well due to the axial symmetry of the close-packed structure. For the thirty-two port devices investigated, however, axial symmetry does not exist which compounds the formation of smooth transition regions and mixer region as well.

For the seven port transmission star, good fusion results were achievable with a single-tipped torch. The initial trials with this torch were unsuccessful on the 19 and 32 port devices. The problem was that the outer two layers of the fiber pack would fuse together almost immediately, while in effect, insulating the inner-most fiber. It proved futile to raise the temperature and attempt to force the fusion process because this invariably led to distortion of the coupler and even parting of some of the fibers. A method of achieving a more uniform heat distribution was called for.

Consequently, a dual tipped torch was fabricated and significantly improved results were obtained. The first device fabricated using this torch was a 32 port transmission star coupler.

An additional benefit of the dual-tipped torch proved to be the balancing of distortion forces as a result of the flame pressure. This fact improved the physical linearity of the devices contributing to the reduction in excess loss.

It is important to note that the dual-tipped torch development was in part responsible for reducing the entrapment of bubbles in the fused coupler region. Cleanliness also plays an important role in bubble minimization by promoting fiber to fiber wetting.

1b. Device Fixturing/Packaging

The approach taken to the fixturing and packaging of these devices was conceived in the interest of device preservation, minimization of handling, and ease of fabrication. This concept utilized a "U" shaped bracket of aluminum where the upper arms were of sufficient length and width to anchor the jacketed fibers securely. The longer the length of fiber that is bonded to the fixture, the better the mechanical isolation provided to the coupler. The distance between the arms of the bracket was determined by the coupler type to be fabricated (greater spacing for couplers fabricated from larger numbers of fibers), and also slightly greater than the stripped fiber length. This distance is important in terms of reducing the angle of taper from the jacketed fibers to the fused coupler.

The stripped and cleaned fiber lengths are cemented individually to the bracket top under a small amount of tension and with no inherent twist. To form the desired packing configuration, short dummy cladded fibers are incorporated into the group to build up the desired structure. The fibers are then drawn together and fused. The tension that existed due to the fiber mounting to the fixture is relieved during fusion. The only tension that remains is that associated with the small contraction of the last zone to be fused.

For the most part, this fixturing/packaging design concept was adequate for this program. However, the thermal expansion coefficient of aluminum relative to fused silica was responsible for breakage of several devices. Increases in temperature above the ambient temperature seen by the package during the fusion process places the coupler in tension with the potential for breakage.

2. Transmission Star Coupler Performance

The measurement data on the transmission star couplers supplied to A.F.A.L. as deliverable items for this program is repeated in Tables 7 through 11. The seven port devices do not represent the best devices or even the mean performance of seven port transmission stars.

Table 12 is the data for one of the best 7-port couplers evaluated during the program. After evaluation, the pigtail leads were too short for further evaluation so that it was not included in the final deliverables.

Table 7. Developmental Model of Seven-Port Star Coupler.

MEASUREMENT DATA ON UNCOATED COUPLER #848

NA=.336	λ=1.05 Microns							
Injected Port	Throughput Level To Receiver Ports							Total Excess (dB) Loss
	B1	B2	B3	B4	B5	B6	B7	
A1	-10.56	-11.21	-12.55	-11.70	-11.09	-11.53	-9.97	-2.71
A2	-10.19	-11.52	-11.92	- 9.33	-10.69	-10.89	-12.60	-2.60
A3	- 9.21	-12.24	-11.38	-9.83	-9.99	-10.03	-12.87	-2.17
A4	-10.31	-10.51	-12.52	-11.40	-11.12	-11.33	- 9.92	-2.49
A5	-11.01	-11.29	-11.51	-11.50	-10.81	-11.15	-10.86	-2.70
A6	- 9.67	-11.85	-10.74	- 9.15	-10.16	-10.87	-12.15	-2.09
A7	- 9.61	-13.38	-10.28	- 8.37	-10.43	-11.31	-14.13	-2.23

MEASUREMENT DATA ON COUPLER COATED
WITH HIGH VACUUM GREASE

	Full NA Injection	λ=1.06 Microns			
Injected Port	λ=	Minimum (dB) Throughput Loss	Maximum (dB) Throughput Loss	Total (dB) Excess Loss	Average (dB) Throughput Loss
B1	.83	-10.67	-13.07	-3.33	-11.78
	1.06	-10.69	-13.38	-3.43	-11.88
B2	.83	-11.80	-17.45	-4.54	-12.99
	1.06	-11.72	-17.46	-4.55	-13.00
B3	.83	-10.92	-14.44	-4.05	-12.50
	1.06	-11.01	-14.94	-4.32	-12.78
B4	.83	-8.70	-13.46	-2.30	-10.75
	1.06	-8.66	-13.39	-2.22	-10.67
B5	.83	-11.19	-14.04	-3.78	-12.23
	1.06	-11.43	-14.23	-3.98	-12.43
B6	.83	-10.74	-15.42	-3.84	-12.29
	1.06	-10.86	-15.66	-4.03	-12.48
B7	.83	-11.18	-18.79	-4.33	-12.78
	1.06	-11.31	-19.00	-4.45	-12.90

Table 8. Developmental Model of Seven-Port Star Coupler.

MEASUREMENT DATA ON COUPLER (#827) COATED

WITH SYLGARD 184

PORT TO PORT THROUGHPUT (dB)

INJEC-TED PORT	λ = 1.06 MICRONS NA	A1	A2	A3	A4	A5	A6	A7	TOTAL EXCESS LOSS (dB)	AVERAGE THROUGH-PUT (dB)
B1	.243	-11.75	-12.19	-12.48	-11,54	-14.61	-12.63	-14.96	- 4.26	-12.71
	.336	-11.81	-12.26	-12.54	-11,70	-14.68	-12.82	-15.04	- 4.36	-12.81
B2	.243	-10.52	-11,54	-11.50	-11,74	-14.27	-12.18	-14.89	- 3.52	-11.97
	.336	-10.92	-11.76	-11.74	-11,03	-14.55	-12.11	-14.97	- 3.75	-12.20
B3	.243	-11.28	-11.39	-12.36	-11.56	-14.12	-12.72	-14.94	- 3.99	-12.44
	.336	-11.73	-11.91	-12.65	-11.85	-14.39	-13.17	-15.25	- 4.37	-12.82
B4	.243	-10.32	-10.95	-11.52	-10.59	-13.25	-11.84	-14.38	- 3.19	-11.64
	.336	-10.67	-11.25	-11.80	-10.86	-13.59	-11.99	-14.50	- 3.46	-11.91
B5	.243	-11.05	-11.58	-12.24	-11.05	-13.80	-12.32	-14.69	- 3.76	-12.21
	.336	-11.40	-11.94	-12.52	-11.31	-14.02	-12.58	-14.97	- 4.06	-12.51
B6	.243	-11.03	-11.35	-11.92	-11.16	-12.93	-12.27	-14.32	- 3.56	-12,02
	.336	-11.02	-11.35	-12.10	-11.11	-12.95	-12.37	-14.66	- 3.65	-12.11
B7	.243	-11.20	-11.58	-12.17	-11.26	-13.90	-12.21	-14.80	- 3.82	-12.27
	.336	-12.02	-12.02	-12.51	-11.58	-14.37	-12.62	-15.31	- 4.30	-12.75

Table 9. Developmental Models of 19-Port Star Couplers.

MEASUREMENT DATA ON COUPLER (#911) COATED WITH SYLGARD 184

Full NA Injection λ = .83 Microns

Injected Port	Minimum (dB) Throughput Loss	Maximum (dB) Throughput Loss	Total (dB) Excess Loss	Average (dB) Throughput Loss
A1	-13.59	-23.20	-4.17	-16.95
A2	-14.88	-21.65	-5.35	-18.14
A3	-14.23	-22.65	-4.53	-17.32
A4	-13.59	-21.92	-4.25	-17.04
A5	-11.79	-23.29	-3.99	-16.77
A6	-17.53	-29.07	-8.97	-21.76
A7	-14.75	-23.20	-5.20	-17.99
A8	-16.67	-25.15	-7.15	-19.94

MEASUREMENT DATA ON COUPLER (#912) COATED WITH SYLGARD 184

NA = .336 λ = 1.05 microns

Injected Port	Minimum (dB) Throughput Loss	Maximum (dB) Throughput Loss	Total (dB) Excess Loss	Average (dB) Throughput Loss
A1	-12.58	-24.51	-4.45	-17.23
A2	-15.27	-24.92	-6.16	-18.94
A3	-13.36	-26.44	-4.38	-17.16
A4	-12.06	-27.31	-3.71	-16.50
A5	-15.08	-23.68	-5.16	-17.95
A6	-13.90	-25.64	-4.36	-17,96
A7	-12.63	-25.79	-4.85	-19.57
A8	-12.70	-26.79	-2.51	-16.72

Table 10. Development Model of 32-Port Star Coupler.

MEASUREMENTS DATA ON UNCOATED COUPLER (#922)

Injected Port	λ = (Microns)	Minimum (dB) Throughput Loss	Maximum (dB) Throughput Loss	Total (dB) Excess Loss	Average (dB) Throughput Loss
A1	.83	-26.66	-32.03	-13.51	-28.57
	1.06				
A2	.83	-18.30	-24.77	- 5.59	-20.65
	1.06	-19.30	-26.20	- 6.80	-21.85
A3	.83	-16.51	-23.01	- 4.52	-19.57
	1.06				
A4	.83	-18.61	-23.33	- 4.81	-19.87
	1.06	-19.81	-23.75	- 6.02	-21.07
A5	.83	-19.26	-24.48	- 6.04	-21.09
	1.06	-20.19	-25.45	- 7.15	-22.21
A6	.83	-18.12	-23.91	- 4.91	-19.96
	1.06	-18.72	-24.23	- 5.81	-20.85
A7	.83	-19.23	-23.57	- 6.45	-21.50
	1.06	-19.27	-23.55	- 6.59	-21.63
A8	.83	-17.94	-25.24	- 5.48	-20.53
	1.06	-18.57	-25.81	- 6.18	-21.23
A9	.83	-19.74	-23.87	- 6.30	-32.35
	1.06	-20.04	-24.01	- 6.64	-21.69
A10	.83	-17.97	-24.01	- 5.23	-20.28
	1.06	-18.42	-24.60	- 5.69	-20.74
A11	.83	-19.61	-24.38	- 6.30	-21.35
	1.06	-18.47	-24.31	- 6.28	-21.33
A12	.83	-15.84	-25.19	- 3.77	-18.82
	1.06	-17.11	-24.38	- 5.11	-20.16
A13	.83	-21.54	-25.62	- 8.17	-23.22
	1.06	-21.77	-25.53	- 8.72	-23.77

Table 11. Developmental Model of 32-Port Star Coupler.

MEASUREMENT DATA ON COUPLER (#913)

COATED WITH HIGH VACUUM GREASE

INJECTED PORT	λ= (MICRONS)	MINIMUM (dB) THROUGHPUT LOSS	MAXIMUM (dB) THROUGHPUT LOSS	TOTAL (dB) EXCESS LOSS
A3	.83	-19.30	-24.37	-6.01
	1.06	-20.16	-25.18	-6.75
A4	.83	-20.46	-24.80	-6.48
	1.06	-20.93	-25.21	-6.96
A5	.83	-20.84	-25.21	-6.84
	1.06	-21.23	-25.63	-7.18
A6	.83	-20.66	-25.59	-7.19
	1.06	-21.22	-25.77	-7.45
A7	.83	-20.05	-26.42	-6.40
	1.06	-20.49	-25.57	-7.10
A8	.83	-14.27	-18.25	- .36
	1.06	-15.33	-19.69	-1.78
A9	.83	-17.19	-24.16	-4.49*
	1.06	-18.44	-25.62	-6.45*
A10	.83	-17.42	-22.39	-3.96*
	1.06	-17.61	-23.94	-5.22*
A11	.83	-19.94	-24.83	-6.44*
	1.06	-18.26	-22.85	-4.52*

*The .83 micron source was showing intermittent output when these measurements were made and the excess loss discrepancies are probably due to this problem. The 1.06 micron values are more reliable in these cases.

Table 12. Seven-Port Transmission Star #802.

Port #	Throughput Losses dB			Excess (dB)
	Avg	Min	Max	
1	-11.67	-10.81	-12.60	-3.17
2	-10.98	-10.00	-12.10	-2.47
3	-11.49	-10.65	-12.27	-2.99
4	-11.57	-10.90	-13.10	-3.06
5	-11.99	-10.88	-13.12	-3.46
6	-11.24	-10.19	-14.54	-2.60
7	-11.35	-10.42	-12.80	-2.84

The data presented in these tables indicate, at least at the present level of technique development, that

- o Cladded coupler performance was not as good as uncladded, at least for 7-port devices, and
- o Excess losses increase with increasing number of fibers in the coupler

The role of mode conversion and reconversion in cladded and uncladded couplers has been discussed in Section III, 5. This effect has been observed in directional couplers and 7-port stars by measurements on the same coupler in both states. However, similar measurements were not made on 19- and 32-port couplers; consequently definite conclusions as to mode conversion effects cannot be made for these devices. The data on the two 32 port devices, one cladded and one uncladded, could be construed as indicating a reduced effect. However, variation between the couplers seems a more reasonable explanation as to the similar throughput results.

Excess loss dependence on number of fibers does seem to be evident, especially when data on directional couplers is considered. This is not particularly surprising with the present fabrication techniques. The overall physical distortion in making couplers with large numbers of fibers is greater because of the necessity of transition from the jacketed region to the region to be fused. Figure 13 depicts the excess losses vs. number of fibers in the couplers for some of the devices fabricated during this program.

3. Reflection Star Coupler Fabrication

Both reflection and transmission stars were to be developed under this program. However, handling difficulties were encountered with the extra processing steps required to make reflective devices that were not overcome during the course of the program. At least part of the problem was associated with the package configuration requiring pigtails for evaluation purposes.

The procedure for fabricating reflection star couplers was identical to that for transmission devices for the first stages. Once the equivalent of a transmission device had been formed, the coupler was broken into two pieces near the center of the fused region. The resulting end of one-half was then to be prepared with a flat and perpendicular end fuse suitable for coating with a high reflectance metal, for example with the silver coating technique described in Section II, 7.

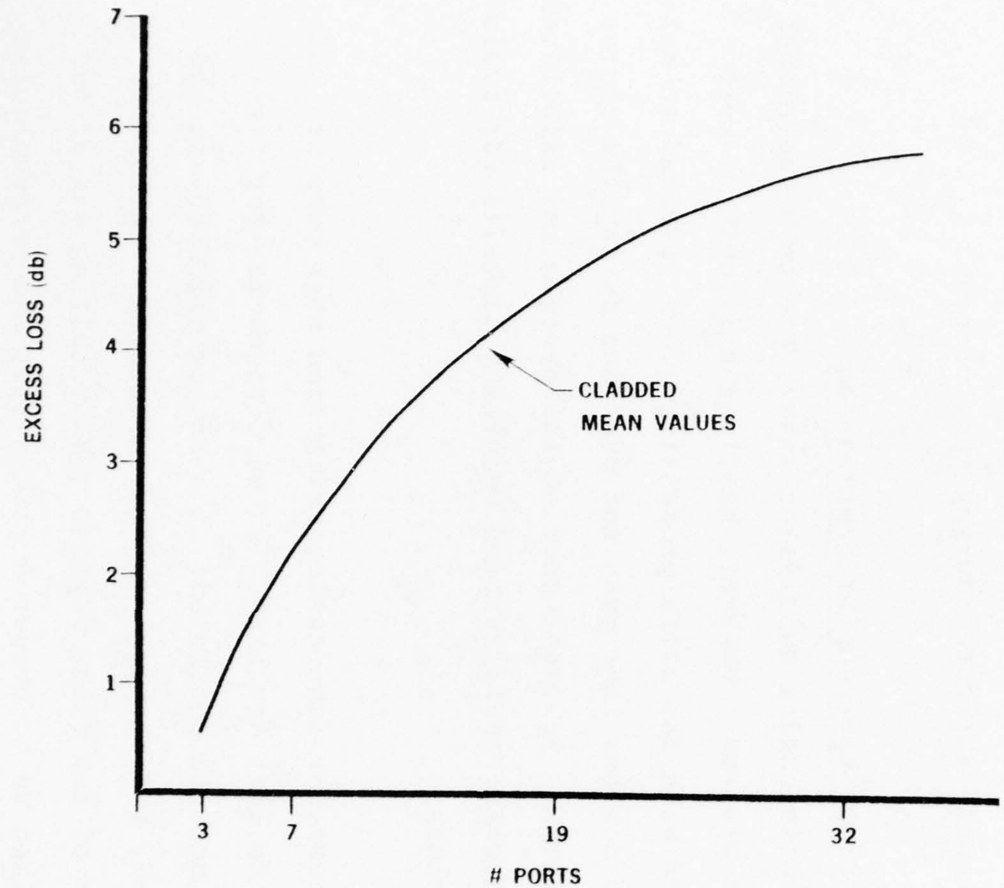

Figure 13. **EXCESS LOSS VS. # OF PORTS** 302 10725

The problem that prevented successful fabrication was that of preparing a suitable end face. Initial attempts to accomplish this by separating the two halves by a scribe and break technique were not successful. The resulting end face was not sufficiently flat and perpendicular for good device operation.

Once the scribe and break technique was found not to be suitable a number of other approaches using polishing techniques were attempted. However, these all involved the necessity of holding the coupler end firmly and polishing under the handicap of having the pigtails dangling from the opposite end of the package. This presented a clumsy fixturing problem as well as difficulties in finding suitable methods to stabilize the coupler region itself during polishing. Various materials were either tried or considered for potting during the polishing, but they either proved too soft to adequately protect the coupler from breaking, or could not be removed sufficiently after polishing in order to restore the coupler guiding characteristics. Breakage was caused by stresses induced through the pigtails to the transition region.

Although this effort was unsuccessful, the principal element in achieving a useful device appears to have been identified.

Coupler sections formed from short lengths of fiber close-packed without bending stresses can be easily achieved. Because of the extremely light mass and absence of pigtail sections to cause breakage, these coupler sections can be easily potted or handled in other ways so as to successfully finish the end face.

Thus the coupler section itself can be fabricated. In order to be useful a suitable package concept is required to allow its actual integration into a system or test set-up. The basic considerations for such a new package design are discussed in Section VI, 2. As outlined there, the new package design has other favorable characteristics with respect to improving overall coupler performance.

4. Conclusions

Transmissive star couplers using 7, 19 and 32 fibers were successfully fabricated by direct fusion of the coupler region in bare silica fibers. With current techniques the excess loss levels were sufficiently low to encourage data bus system development using these couplers. Excess losses less than 3.0 dB were observed in 7-fiber devices, while the excess losses in 19 and 32 fiber devices were significantly reduced over the course of the program to levels approaching realistically usable values. Excess losses of 5.0 and 7.0 dB, respectively, are achievable. Uniformity of output of 7-port devices appears to be well with ±1 dB.

The improvement in coupler performance with technique improvement was accompanied by obvious improvement in coupler appearance in the transition and coupler regions. Since observation of these regions in good couplers still indicates that significant distortions exist, it appears that improved fabrication techniques may yield still better results.

Some of the unwanted physical distortions that appear in the coupler appear to be due to the present packaging approach which requires compacting of fibers from the jacketed configuration down to the region where fusion occurs. This process appears to induce residual stresses which result in distortion during fusing. Fabrication of couplers from short lengths of bare fiber should reduce or eliminate this effect. The packaging requirements for devices fabricated this way have been mentioned in the previous section and are discussed in some detail in Section VI, 2.

Reflective star couplers should also be amenable to fabrication by these techniques as discussed in Section V, 3. It is expected that excess losses for the reflective devices will be approximately 1 dB greater than in the transmissive devices.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

1. General Conclusions

The previous sections have described in detail the fabrication techniques and processes developed to form couplers for fiber optic data bus applications by the direct fusion of uncladded PCS fibers. The pertinent results of devices actually fabricated and evaluated have also been presented. On the basis of these results, it appears that the following conclusions can be justified:

- O The fiber fusion process is a generally viable technique for fabricating low-loss couplers for data bus applications;
- O Excess losses due to core/clad ratios and packing fraction can be eliminated (at least in some cases) with only minor excess losses incurred due to transitioning regions in the coupler;
- O Splitting ratios in directional couplers and output variability in star couplers can be kept within fairly tight tolerances;
- O Using current techniques there appears to be some problem in "T" couplers associated with modal distribution.

In particular, the data for the directional couplers and the 7-port transmission stars show that excess losses can approach very low values ($\sim$.3 and 2.0 dB respectively) and that with the techniques used at the end of the program, typical losses can be .6 and 3.0 dB respectively. The data on 19-port transmission stars and even the 32-port devices also indicate that technique improvements over the course of the program had a significant effect in reducing fabrication related losses. As indicated earlier, stress related residual geometry defects appear to now be a major loss factor. If the stress can be further reduced, as is expected in a new package design to be discussed in Section VI, 2, then the apparent dependence of excess loss on the number of fibers in the coupler may be significantly reduced.

Even at the present level of technique development, the control of splitting ratios in directional couplers and uniformity in stars appears to depend to a signficant degree on the diameter control of the fibers used in the coupler. Thus, even though these parameters already appear to be under good control, there is potential for further improvement with improved fiber diameter control.

The one parameter which seems to be least under control at the present time, as evidenced in particular by the results with the "T" couplers, is the coupling modal distribution in directional couplers. Although this appears to represent a significant loss element in "T" couplers, and may have a measurable effect when the other couplers are evaluated in full systems, it can be expected that further improvement will be obtained with additional effort.

In summary, the results of this program are that

- o Direct fusion of fiber core material is a viable technique for coupler fabrication;
- o Usable directional couplers and 7-port transmission stars have been developed under this program.

2a. Recommendations for Future Development

Over the course of this program, and based on the results reported in earlier sections, it became apparent that final package design for direct fusion couplers would become an important factor both in coupler processing and fabrication and in optical, mechanical, and environmental performance. Consequently an important result of this program has been the evolution of a package design concept which is recommended as a part of future development efforts. In Section VI, 2b, the factors leading to this recommendation are reviewed, the design concept is presented, and expected improvements associated with the new design are discussed.

Finally, with the advance in basic coupler technology represented in this program, and in particular the delineation of practical performance levels expected, it appears that more detailed study of other systems components and the expected performance level of specific fiber optics data bus systems is in order. This topic is discussed briefly in Section VI, 2c.

2b. Package Design Considerations

The following factors have emerged as important elements in the consideration of final package design for the couplers developed initially in this program:

- Reduction of residual stresses inherent in current packaging techniques
- Improving throughput characteristics by allowing the use of uncladded coupler regions
- Removal of pigtails as an important failure mechanism due to transferral of external stresses
- Reduction of differential thermal expansion as a potential source of environmentally produced failure
- Consideration of connector requirements as an integral part of the package, especially for star couplers.

The first of these factors has been discussed in previous sections of this report; the residual stresses involved appear to be directly related to the necessity for a transition region from the jacketed fiber configuration to the compacted region where fusion takes place. The presence of pigtails hanging on the outside of the support structure may also be a factor. Elimination of these stresses appears to be desirable for both mechanical and optical performance requirements. Thus it appears that reduction of residual stresses can be achieved only through fusion of short bare fibers without bends.

The generally better optical performance of couplers in the uncladded state as indicated by the data on the individual couplers has been discussed. It appears to be due to retention in the coupler region of upconverted modes from the input fibers which would be lost if the coupler region were cladded. These then appear to be downconverted into the fiber outputs. Although it appears probable that this effect would be reduced if the finished coupler geometry is improved in other respects, it should remain a consideration, at least for the present, because of its potential impact on coupler performance. The resulting implication for the package is an open internal design which can be sealed from outside environmental effects.

The resiliency of the cladding material used in PCS fibers is sufficient to allow measurable movement of the fiber core relative to the outer jacket under bending conditions. This translates into an externally imposed stress at the transition from individual, separated fibers to the fused region. Since this area appears to be significantly reduced in strength, manipulation of the pigtail fibers becomes a source for potential coupler failure. On this basis the elimination of pigtails seems to be called for.

Differential thermal expansion between the fused silica coupler/fiber combination and the basic package mount is expected to be a potential failure mechanism due to imposed stress for couplers used in extreme temperature environments. Thus a major consideration is the choice of basic material to be used for any new package design.

Finally, at least in the case of the star couplers, the large number of individual fibers leads to a potentially significant material and installation cost if termination is made with single fiber connectors. Thus a new package design should provide the capability for incorporating an integral connector. This should also lead to a significant size reduction.

All of these factors can be taken into proper consideration by using an integrated coupler/connector package concept. Bent fibers are eliminated as a source of residual stresses, pigtail fibers are eliminated as both a source of residual fabrication stresses and externally induced stress failure, and the direct integration of a single alignment mechanism, multiway connector is accomplished. Once an integrated package concept is accepted, the coupler can be left uncladded provided the package is appropriately sealed. This does not appear to present a significant problem. Finally, the central support element in the package can be chosen from a wide variety of materials to meet the thermal expansion requirement.

It is expected that an integrated package as discussed above will result in:

- Small package size
- Improved throughput
- Improved modal distribution
- Capability of mating to glass-glass fibers with the use of a transition element.

The small package size is achieved primarily by elimination of the requirement for an external mounting surface for single or multi-way connectors. Throughput improvement results from

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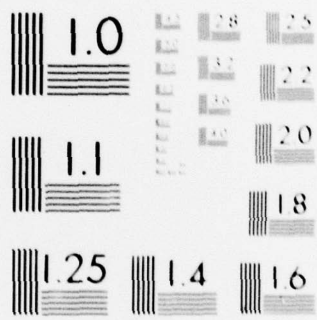

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elimination of internal cladding and reduction of residual stresses while the latter may be expected to result in better modal distribution. The central coupler element may be used, with the aid of a transition element, in data bus systems using glass-glass fibers instead of PCS. Although design of an appropriate transitioning element is only at the concept stage, it should be readily implementable in this package concept.

Two additional benefits should result from the use of a new package concept:

- Reduction of excess losses in "T" couplers
- Capability of fabricating reflection star couplers.

2c. System Considerations

The development of practical couplers for single fiber data bus systems has reached the level where detailed design information will soon be required. Detailed system design study must be conducted in order to determine real coupler requirements. Specifically, fiber type and core size, directional coupler splitting ratios, "T" coupler distribution ratios, transmission or reflection coupler and number of ports required need to be determined in detail. Among the elements that must be considered are:

- Basic System Topology
- "T" vs Star Distribution
- Uni- or Bi-Directional Fiber Transmission
- Redundancy Requirements
- Source-Fiber Coupling Efficiency vs Core Size
- Fiber Transmission and Mechanical Characteristics vs Core Size
- Economic trade-offs concerning proliferation of specific coupler designs
- State-of-Art Coupler Performance

Coupler state-of-art for system design considerations can be considered to be:

- Directional Couplers

Excess Losses:	0.7 dB
Maximum splitting ratio:	-14 ±2 dB
Minimum splitting ratio:	3 dB (plus excess)

Maximum splitting ratio will change according to

$$-20 \log_{10} \frac{30}{d}$$

where d is fiber core diameter in μm.

o "T" Coupler

Excess losses:	3.0 to 4.0 dB
Maximum Splitting Ratio:	-14 ±2.0 dB
Minimum Splitting Ratio:	3 dB + excess

Maximum Splitting ratio will change according to

$$-20 \log_{10} \frac{30}{d} .$$

Excess losses can be expected to approach 2 dB with technique development.

o Transmission Star Coupler

Excess Loss:	7-port	3.0 dB
	19-port	5.0 dB
	32-port	7.0 dB

Minimum Fiber Size approximately 50 μm

o Reflection Star Coupler (Projected)

Excess Loss:	7-port	4.0 dB
	19-port	6.0 dB
	32-port	8.0 dB

Minimum Fiber Size approximately 50 μm

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